

**A COMPARISON OF TWENTY SIMULATED STRATEGIES FOR ACHIEVING
MAXIMUM PARTS VALUE RECOVERY IN OPTIMIZING CHOP SAW
OPERATIONS.**

by

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ABSTRACT

A simulation model, using a dynamic program and other functions, successfully emulated an automated chop saw that cuts, from a sample mill, full length lumber into usable parts according to a cutting bill. The program determined if value recovery per board foot (value/fbm) from a mill run could be increased by modifying the chop saw's priority settings which forced parts into a cutting solution. Twenty different cutting algorithms were employed of which 18 prioritized up to three different parts, one was based on the sample mill's priority settings and the remaining one was a control or regular optimization. Each algorithm scanned the cutting bill to dynamically update priority settings, using the value of pieces remaining to be cut as a deciding factor each time a full length board was processed. Production was stopped on parts which had reached a certain production point or cutoff percentage. Data, consisting of grades and lengths of all lumber sections from two dimensions, 3" width and 3.75" width, were put into a simulation model for processing. Students-Newman-Keuls tests showed that there was no single algorithm that performed decisively better than others. The highest rated cutting algorithm prioritized three different parts and forced one of each part into a cutting solution with an 80% cutoff percentage. Further data analysis proved that good value/fbm results were not obtained by using more infeed lumber or sacrificing parts recovery percentage.

Key Words: chop saw, cutting algorithms, dynamic program, optimization, priority settings, simulation.

TABLE OF CONTENTS

A Comparison Of Twenty Simulated Strategies For Achieving Maximum Parts Value Recovery In Optimizing Chop Saw Operations.

ABSTRACT	ii
LIST OF TABLES.....	vi
LIST OF FIGURES.....	vii
ACKNOWLEDGEMENTS	viii
UNIVERSITY OF BRITISH COLUMBIA (UBC):	viii
Committee Members	viii
Other Contributors.....	viii
INDUSTRY:.....	viii
1.0 INTRODUCTION	1
1.1 BACKGROUND AND OBJECTIVES	1
1.2 CHOP SAW TECHNOLOGY AND LITERATURE REVIEW	2
1.2.1 Grades and Dimensions of Lumber Parts	3
1.2.2 Prices Of Lumber Parts.....	4
1.2.3 Input Lumber.....	5
1.2.4 Lumber Defect Detection	6
1.2.5 Infeed.....	8
1.2.6 Cutting Mechanism.....	8
1.2.6.1 Manual.....	8
1.2.6.2 Semi-Automated.....	9
1.2.6.3 Automated	9
1.2.7 Sorting	10
1.2.7.1 Completely Manual Sort.....	11
1.2.7.2 Kicker Sorting	11
1.2.8 Chop Saw Software Options.....	12
1.2.8.1 Simulation	12
1.2.8.2 Modify Priority Settings.....	12
1.3 MACHINERY SETUP	15
2.0 MATERIALS AND METHODS	18
2.1 DESCRIPTION OF THE TEST MILL.....	18
2.1.1 Mill Operation	18
2.1.2 Raw Material	20
2.1.2.1 3" Width Lumber.....	20
2.1.2.2 3.75" Width Lumber.....	21
2.1.3 Products	21
2.1.4 Costs	21
2.2 DATA COLLECTION	22
2.2.1 Lumber Data.....	23
2.2.2 Time and Motion Study	23
2.2.3 Data From Mill Employees	24
2.2.4 Yield Data.....	25
2.2.4.1 Basic Structure.....	25
2.2.4.2 Modifications To Demand.....	26
2.2.4.2.1 Actual Cut.....	27
2.2.4.2.2 Actual Demand.....	27
2.2.4.2.3 Pseudo Demand.....	28
2.3 DEVELOPMENT OF CHOP SAW ALGORITHMS	29

2.4 SIMULATION PROCEDURES.....	30
2.4.1 Graphical Elements Of The Chop Saw Simulation Model.....	32
2.4.1.1 Lumber Movement.....	32
2.4.1.2 Downtime.....	33
2.4.2 C Program Inserts Of Chop Saw Simulation Model.....	35
2.4.2.1 Assigning Lumber Data.....	35
2.4.2.1.1 Get Board Number/Selection Information.....	36
2.4.2.1.2 Select Board.....	37
2.4.2.1.3 Select Interarrival Time.....	39
2.4.2.2 Making Cutting Decisions.....	39
2.4.2.2.2 Get The Best Cutting Pattern.....	42
2.4.2.2.3 Dynamic Program.....	44
2.4.2.2.3.1 Features Common To Both Cutting Modes.....	44
2.4.2.2.3.1.1 Accuracy.....	44
2.4.2.2.3.1.2 Fingerjointing.....	44
2.4.2.2.3.1.3 Cutting Considerations.....	45
2.4.2.2.3.2 Features Applicable Only To Actual Cutting.....	46
2.4.2.2.3.2.1 Statistics From Each Board.....	46
2.4.2.2.3.2.2 Kicker.....	47
2.4.2.2.3.2.3 Intervention.....	47
2.5 DATA ANALYSIS.....	49
2.5.1 Analysis Variables.....	49
2.5.1.1 Value Recovery Per Fbm.....	49
2.5.1.2 Number Of 20' Clears Added.....	50
2.5.1.3 Percent Recovery Of Parts.....	50
2.5.1.4 Number Of Boards Processed.....	51
2.5.2 Setup Of Analysis.....	51
2.5.2.1 2 Way Anova Description.....	51
2.5.2.2 Student-Newman-Keuls Range Test.....	53
2.5.3 ANOVA Assumptions.....	53
2.5.3.1 Normal Data.....	53
2.5.3.2 Repeatable Process.....	54
2.5.3.3 Homogeneous Variances.....	54
2.5.4 Comparing Analysis Variables.....	54
3.0 RESULTS AND DISCUSSION.....	56
3.1 3.75" WIDTH LUMBER.....	56
3.2 3" WIDTH LUMBER.....	57
3.2.1 Value/Fbm Means.....	57
3.2.1.1 Differences.....	58
3.2.1.2 Number Of Parts Prioritized.....	60
3.2.1.3 Cutoff Percentages.....	61
3.2.2 Interaction Results.....	61
3.3 3" WIDTH EXTERNAL VARIABLES.....	62
3.3.1 Number Of 20' Clears Added.....	63
3.3.2 Number Of Boards Processed.....	66
3.3.3 Percent Recovery Of Parts.....	70
3.4 3" WIDTH FINANCIAL BENEFITS OF THE IDEAL ALGORITHM.....	73
4.0 SUMMARY AND RECOMMENDATIONS.....	75
4.1 SUMMARY.....	75
4.2 RECOMMENDATIONS.....	76
5.0 LITERATURE CITED.....	78
APPENDIX I. DATA FROM BOTH GRADES OF LUMBER.....	80
APPENDIX II. PROJECT CUTTING BILLS.....	81
APPENDIX III. DOWNTIME DATA.....	86

APPENDIX IV.	FINGERJOINTING RULES.....	87
APPENDIX V.	TWO WAY ANOVA PROCEDURES.....	88
APPENDIX VI.	BARTLETT'S TEST PROCEDURES/EXAMPLE	90
APPENDIX VII.	SNK PROCEDURES/EXAMPLE	92
APPENDIX VIII.	3.75" WIDTH DATA MATRIX	93
APPENDIX IX.	3" WIDTH VALUE/FBM MEANS DATA MATRIX	94
APPENDIX X.	3" WIDTH VALUE/FBM - BARTLETT'S TEST	95
APPENDIX XI.	20' CLEARS ADDED DATA MATRIX	96
APPENDIX XII.	3" WIDTH NUMBER OF 20' CLEARS ADDED - BARTLETT'S TEST.....	97
APPENDIX XIII.	3" WIDTH 20' CLEARS ADDED (INTERVENTION) - SNK	98
APPENDIX XIV.	3" WIDTH NUMBER OF BOARDS PROCESSED DATA MATRIX	99
APPENDIX XV.	3" WIDTH NUMBER OF BOARDS PROCESSED - BARTLETT'S TEST	100
APPENDIX XVI.	3" WIDTH NUMBER OF BOARDS PROCESSED - SNK	101
APPENDIX XVII.	3" WIDTH PERCENT PARTS RECOVERY DATA MATRIX	102
APPENDIX XVIII.	3" WIDTH PERCENT PARTS RECOVERY - BARTLETT'S TEST	103
APPENDIX XIX.	3" WIDTH PERCENT PARTS RECOVERY - SNK	104
APPENDIX XX.	3" WIDTH YEARLY VALUE DIFFERENCES FROM ALGORITHM 14.....	105
APPENDIX XXI.	EXAMPLE OF 3 WAY VALUE/FBM ANOVA SETUP	106

LIST OF TABLES

Table 1. Example of A Cutting Bill.....	13
Table 2. Production Results From A 180" Usable Section.....	14
Table 3. 3" Width Lumber:.....	20
Table 4. 3.75" Width Lumber:.....	21
Table 5. Actual Chop Saw Cutting Bill.....	25
Table 6. "Actual Cut" Cutting Bill Demand.....	27
Table 7. Pseudo Demand Example.....	29
Table 8. Cutting Algorithms.....	30
Table 9. C Program Steps To Obtain Lumber Information.....	36
Table 10. Sample Of Lumber Identification File.....	36
Table 11. Lumber Package Length Composition Rules.....	37
Table 12. Example Of Board Data File.....	38
Table 13. Cumulative Distribution Of Interarrival Times For 10' Lumber.....	39
Table 14. Example Of Fingerjoint Rules (3" Width - Cutbill #6).....	45
Table 15. Example Of Simulation Run Summary Report.....	46
Table 16. Example Of Board Data File.....	47
Table 17. Example Of 3" Width Value/Fbm Table.....	52
Table 18. Example Of Average Value/fbm versus Average Number Of Boards Processed Data.....	55
Table 19. ANOVA Table For 3.75" Width Lumber.....	56
Table 20. ANOVA Table For 3" Width Lumber.....	57
Table 21. 3" Width Value/Fbm Bartlett's Test Results.....	58
Table 22. 3" Width Number Of 20' Clears Added ANOVA.....	63
Table 23. 3" Width Number Of 20' Clears Added Bartlett's Test Results.....	63
Table 24. Number of Boards Processed ANOVA.....	67
Table 25. 3" Width Number of Boards Processed Bartlett's Test Results.....	67
Table 26. Percent Recovery Of Parts ANOVA.....	70
Table 27. 3" Width Percent Recovery Of Parts Bartlett's Test Results.....	70

LIST OF FIGURES

Figure 1. Chop Saw Input (A) and Outputs (B).....	3
Figure 2. Sequence Of Common Chop Saw Features	5
Figure 3. Example Of Board Grading System.....	19
Figure 4. Steps To Acquire Lumber Data.....	23
Figure 5. Illustration Of Lumber Grading Station	24
Figure 6. Discrete Simulation Example Using Normal Distribution	31
Figure 7. Full Length Lumber and Parts Flow Networks.	33
Figure 8. Downtime Networks	34
Figure 9. Diagram Of Board From Row 207 In Table 12	38
Figure 10. Flowchart Of Procedures For Cutting Parts From Full Length Lumber	40
Figure 11. Cutting Algorithm and Cutting Pattern	41
Figure 12. Example Of Board Scanning.....	42
Figure 13. Cutting Patterns For Test Mode	43
Figure 14. Rankings Graph Example - Value/fbm Versus Number Of Boards Processed.....	55
Figure 15. 3.75" Width Value/fbm	57
Figure 16. Student-Newman-Keuls Comparison Of Means Table	59
Figure 17. 3" Width Value/FBM Means	59
Figure 18. Cutting Prioritized Parts With Algorithms 10, 11, and 12	60
Figure 19. 3" Width Interaction Plot	62
Figure 20. Interaction - Average Number Of 20' Clears Added	64
Figure 21. Average Number Of Clears.....	65
Figure 22. Rank Comparisons - Number Of 20' Clears Added Vs. Value/fbm	66
Figure 23. Interaction - Average Number Of Boards Processed	68
Figure 24. Average Number Of Boards Processed.....	68
Figure 25. Rank Comparisons - Average Number Of Boards Processed Vs. \$/fbm	69
Figure 26. Interaction - Average Percent Recovery Of Parts	71
Figure 27. Percent Recovery Of Parts	72
Figure 28. Rank Comparisons - Percent Recovery Of Parts Vs. \$/fbm.....	73
Figure 29. Yearly Value Differences From Algorithm 14.....	74

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1.0 INTRODUCTION

1.1 Background and Objectives

For as long as furniture and homes have been built there has always been demand for attractive and durable lumber parts. Derived from full-length lumber after undesirable characteristics have been crosscut out by machines known as optimizing chop saws, lumber parts are subject to processes such as trimming, sanding, moulding, and gluing before contributing to a finished product. Grading rules restrict the characteristics of allowable lumber defects while a cutting bill or list of parts wanted by a customer influences chop saw cutting decisions.

The objective of this thesis project was to find the cutting algorithm among the twenty proposed that achieved the highest value per board foot (value/fbm) figure. Three properties of a cutting bill, priority settings, prices, and quantities of parts demanded were the main criteria under study in this project, although many other aspects of chop sawing could have been included. Data taken from a sample mill from several cutting bills from two dimensions of lumber was used to confirm the validity of the chosen algorithm.

A simulation program was developed to analyze modifications made to conventional methods of changing priority settings in an optimizing chop saw using methods such as remaining value to select parts and updating parameters each time a board is processed. The model was based on actual mill data and emulated the process from lumber grading to parts tallying.

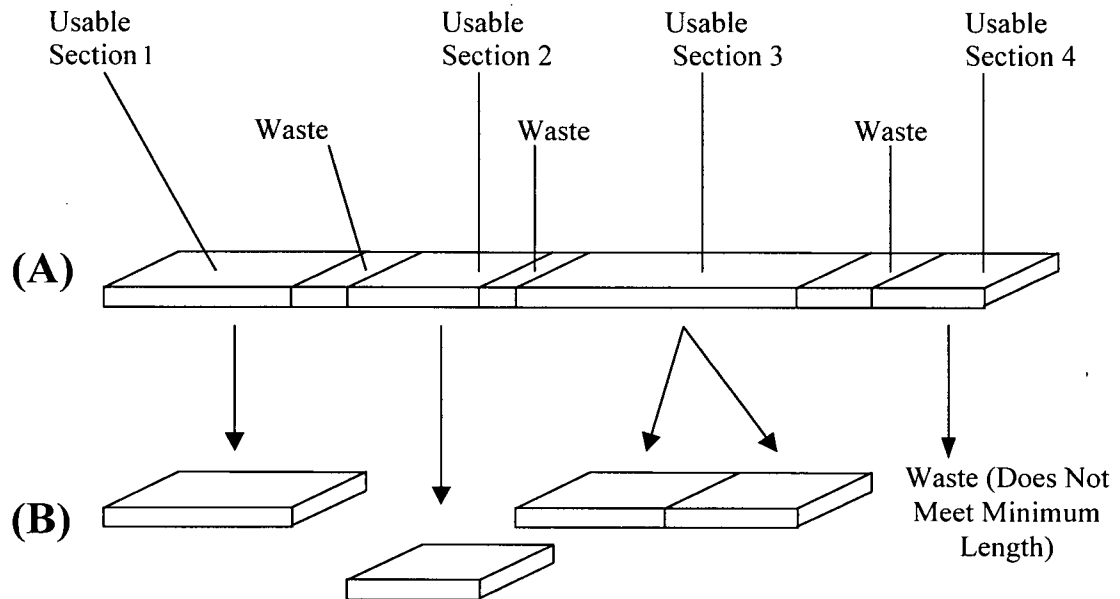
Once all information was gathered and organized, established statistical tests determined the best algorithm. Further analysis was done on three other chop saw run variables (external variables) to see if high value/fbm figures came at the expense of other chop saw run properties. Calculations, based on lumber volume data from the project mill, derived the financial benefits of the recommended algorithm.

A literature search was conducted to complement the thesis and ensure that the work differed from previous projects. Therefore, references to previous work have been made throughout the current chop saw technology section where it applied directly to a certain aspect of chop sawing.

1.2 Chop Saw Technology and Literature Review

Figure 1 shows examples of items that enter (A) and leave (B) a chop saw in which waste or unacceptable sections of the board are separated before any cutting is done (unless defects are irrelevant). Depending on the type of saw and/or the cutting bill (list of parts required by the mill), there may be only one part (Figure 1 - Sections 1 and 2) or more (Figure 1 - Section 3) cut from each usable section. If the defect marking station miscalculated the minimum allowable length, the entire usable section will be treated as waste (Figure 1 - Section 4).

Figure 1. Chop Saw Input (A) and Outputs (B)



1.2.1 Grades and Dimensions of Lumber Parts

Like saw mills producing lumber from logs, chop saw plants employ grading rules for parts that vary significantly between products and customers. An example of grading discrepancy is the tendency for parts destined for use in furniture to require more rings per inch (tighter grain) cross section than input stock allocated for making doors.

Giving even a general definition of grading rules would not provide a realistic view of industry standards. The only generalization that can be made about grading is the tendency for full-length lumber qualities as raw material for secondary manufacturing mills to be at least equivalent to “Shop” grade. Using lumber lower than Shop grade may require excessive use of mill resources and significantly reduce recovery.

Dimensions of parts contributing to certain finished products such as doors and windows are, however, based on established industry standards. Top rails for doors, for example, have widths between 4" and 6" with accompanying lengths between 25" and 47". Parts destined for making window supports have even less dimensional restrictions with a minimum of 3 feet being needed for a cutting.

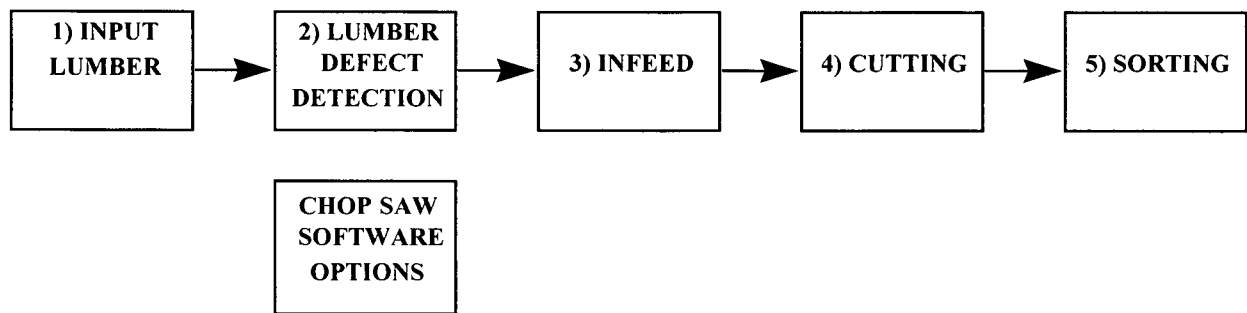
1.2.2 Prices Of Lumber Parts

Each lumber part in a cutting bill has a price associated with it which represents costs incurred in its production and margins for the mill. Depending on the chop saw mill's layout and its system of accounting, costs can be incurred from the following processing stages:

- raw material cost
- lumber drying
- ripping (cut lumber/parts lengthwise)
- chopping
- moulding and/or planing
- handling (labor)
- inventory (cost of keeping part in warehouse)
- additional overhead or fixed/variable costs associated with production

It was deemed inappropriate to use 2 or 3 examples of chop saw setups to generalize existing technology given the large range of lumber inputs and finished products that exist. Making the discussion of chop saws even more complicated is the tendency for basic or simple saws to have selected properties from a sophisticated saw. Therefore, only features commonly seen in chop saws are described here. Figure 2 shows the order in which they often appear. With computer technology significantly changing on an almost annual basis, listed capabilities and limitations should only be seen as examples of what is currently available.

Figure 2. Sequence Of Common Chop Saw Features



1.2.3 Input Lumber

Full length input lumber is almost always kiln dried stock as under or over sized lumber can be easily identified and green or wet lumber is more difficult to cut. Some mills purchase wide faced lumber and rip it into narrower strips which are then cross cut by an optimizing chop saw while others cross cut first. In some cases, mills only apply a minimal amount of planing or edging before the lumber is subjected to cross or rip sawing. There is still no definitive method for processing full length lumber.

Kline *et al* (1993) showed that significant improvements in recovery were possible when furniture parts were produced from unedged and untrimmed lumber. Defect and dimensional data were collected from 120 red oak boards (3 mills) to get objective values on volume of lumber lost to edging and trimming. All data was entered into a “crosscut then rip” based yield optimizing computer program to generate random-width cuttings from numerous edging and trimming scenarios. As expected, volume yields from unedged and untrimmed lumber were the highest, being 25% and 18% higher than those from actual and optimally cut parts from unprocessed lumber, respectively.

Huber *et al* (1983) showed that certain species of “residue” logs or those too short to qualify as standard logs (minimum 8-foot length) and/or too small in diameter to be economically processed in conventional sawmills can be a valuable source of material for resource strapped furniture mills.

Using common industry data, a computer program calculated the point at which the cost of producing a certain volume of lumber parts from short bolts equalled expenses associated with getting the same results with standard lumber grade material break even point. It was found that species producing large yields of lumber parts and those having high value were the most suitable for furniture production as their high break even points allowed for fluctuations in stumpage, harvesting, and bolt sawing costs.

Steele and Gazo (1995) calculated the benefits of sorting lumber prior to rough mill processing or cutting to lumber parts. A simulation program called RAM used rough mill data and six cutting bills to recreate results that would have been yielded from two different mill configurations; crosscut-first (crosscut, straight-line rip, salvage crosscut) and rip-first (gang-rip, crosscut, salvage straight-line rip).

Sorting lumber prior to crosscut-first and rip-first sawing resulted in yield increases of 1 and 0.3 percent, respectively. For crosscut-first sawing, total processing time was not influenced by sorting while rip-first sawing showed a decrease of 2 percent.

1.2.4 Lumber Defect Detection

The value of the eventual end use of the lumber parts dictates the way a mill handles unacceptable lumber defects. If only low grade items such as pallets are being made, then there

may be no need to spend time noting defects. For items with significant value, locations of grade determining flaws must be “marked” out with fluorescent lumber crayons, scanned by cameras, or considered in the board grade.

Systems employing lumber crayons require a worker to observe a board and draw lines perpendicular to the edges to separate defects from usable clear sections. When the crayon marks are detected by a computer vision system, signals are sent to the computer to indicate the starting and ending points. Lengths of sections or boards are derived from calculations that consider elapsed time between two signals and feed speed of the conveyor belt. A less commonly used setup has the lumber grader observing a board and entering locations of defects directly into a computer which in turn stops and conveys the board into the saw to make cuts.

A more expensive and less established defect detection system utilizes an array of color line cameras, each taking pictures of an edge or face to feed video signals back to the chop saw computer. Using digital image processing, the chop saw software processes board picture information before an optimization program calculates the cutting patterns. This system, despite being more accurate and less labor intensive, requires extensive calibration work to correlate colors with lumber properties.

A third technique is to assign a grade to each face of full-length lumber. Crayon marks symbolizing a grade are applied by a worker with the expectation that all the pieces cut from the board are of the same grade. A mill producing furniture parts is an example of an operation that would use only grading or combine it with other defect noting systems.

1.2.5 Infeed

Full length lumber can enter a chop saw either automatically or manually. In a manual setup, the worker removes a board from a lumber queue and positions it against stops or rails before cross cuts are made. Mills which do not require defecting often use a “pack” type of saw where a stack of boards can be cut each time.

Automated infeed saws have a table that moves lumber closer to the cutting area via chains or other means. Once a board is ready to be scanned or cut, top or bottom feed rollers press against its face to provide support during subsequent activities. Positioning accuracy levels of $\pm .004''$ (.1 mm) have been reported by companies selling chop saws equipped with automatic board infeeds. Stating a typical feed speed figure is difficult due to the tendency for input lumber to slow down when cuts are being made.

1.2.6 Cutting Mechanism

In most mills, the lumber parts are chopped out by upward or downward moving saw blades. Automatic saws can reportedly cut with an accuracy between $.031''$ (.8 mm) and $.063''$ (1.6 mm) while the preciseness of manual saws is difficult to gauge. Blade diameters depend on input material but commonly range between 14 and 22 inches. Mill owners have the choice of manual, semi-automated, or completely automated cutting systems, which are described below.

1.2.6.1 Manual

Mills with manual sawing have a number of cutting stations set up next to the bin or queue containing full-length lumber. At each station, a worker manually applies cross cuts to lumber at locations where crayon marks exist. No optimization occurs here - decisions made at the

marking station dictate the size of the parts unless the mill has a trimming station for modifying part lengths.

1.2.6.2 Semi-Automated

Preset cutting sequences or patterns that always cut the same number and dimensions of parts from a given length of lumber are often used by mills that make products where defect location is not a significant factor. An example of preset cutting would be an order having the chop saw cutting five 24" long parts from each 10' board. Benefits from this system include being able to accurately predict when an order quota will be met, minimized waste of input materials, and relative simplicity of the computer software.

1.2.6.3 Automated

Computer optimized cutting where the chop saw makes the "best" cutting decision is required if certain types or dimensions of lumber defects are unacceptable for finished products. After initial scanning to get lengths of usable lumber sections, data is forwarded to a chop saw optimizing program that uses a proprietary algorithm to decide on the resulting parts.

There are two commonly known methods of optimization; exhaustive search and deterministic dynamic programming. Exhaustive search uses loops in a computer program to examine all possible combinations of cuts until the best set is found. Dynamic programming makes decisions recursively using the best solution at the final point. Using these methods, the mill can make longer or higher priced parts a top priority unless user intervention has taken place. Brochures released by chop saw companies claim that yield improvements ranging between 4

and 15 percent can be achieved if a computer based automated cutting system is used instead of a manual one.

A method that is still in its experimental stages is laser cutting where each board is scanned and then subjected to a hot beam capable of producing parts from any location within a board, not just in a cross-cut or rip pattern. Mills adopting this system, known as Automated Lumber Processing System (ALPS), not only eliminate the need for more than one type of saw but also lose less kerf (wood volume equal to the width of the saw blade). The optimization procedures remain the same as those described above.

Klinkhachorn *et al* (1989) applied ALPS to 100 simulated No. 1 and No. 2 Common boards using four cutting bills and 16 algorithms to find that recovery results from the best algorithm ranged from 70.57% to 76.89%. Conventional chop sawing, according to a recent Wood Components Manufacturers study (Wiedenbeck and Scheerer (1996)), obtains an average recovery figure of 61%. Huber (1989) found, based on a comparative analysis, that ALPS was not economically feasible for mills yielding small-sized production levels such as 5 MBF/day. ALPS has still not been fully implemented commercially despite the promising results due to the high cost of its technology and the speed that has been sacrificed to accommodate yield.

1.2.7 Sorting

Once parts have been cut, they are either conveyed directly to stations such as rip or cross-cut saws for further processing or are kept in inventory. Mills that immediately process parts either use sensors or laborers to determine the right path for parts. Operations which store parts rarely use completely automated sorting due to the volume of work involved and the many dimensions

and grades associated with a cutting bill. Below are descriptions of two approaches often used to move parts to pallets for storage.

1.2.7.1 Completely Manual Sort

Lumber parts are conveyed to a table at which workers grade items and put them in the appropriate piles or only transport/organize the parts. Mills with this type of setup often have separate tables or areas for long and short parts to make the job easier for the workers. Even though extra time is spent on categorizing parts according to length, mills with a completely manual sorting chop saw often require less space to install their equipment compared to more automated operations.

1.2.7.2 Kicker Sorting

An alternative setup to a completely manual sort is to have a series of kickers, each responsible for pushing a certain part into a bin, installed along the conveyor belt at the outfeed area of the chop saw. When a part is cut, computer programs combine conveyor belt speed with the distance of the required bin from the cutting area to schedule a time at which the appropriate kicker is to be activated. For example, if a part is cut that belongs to a bin 20' away from the saw and it takes 1.5 seconds to move 1' along the conveyor belt, the designated kicker is programmed to push the part 30 seconds later.

Depending on the mill, kicker sorting still needs manual labor for grading parts and to ensure that cut stock is properly placed on pallets or in containers. In situations where the number of items in a cutting list outnumbers the amount of kickers, additional labor is mandatory for organizing parts at the default bin.

1.2.8 Chop Saw Software Options

Besides making cutting decisions, software from the chop saw manufacturer is often capable of simulating runs and allowing users to modify priority settings.

1.2.8.1 Simulation

Chop saws with this option allow users to estimate the total financial value that could be incurred by a cutting bill before any cutting occurs. Lumber data from a previous run consisting of the dimensions (length and width), crayon mark locations, and positions where cuts were made is incorporated with the regular cutting algorithm and new cutting bill. The number of boards observed by the data collecting mechanism varies between equipment manufacturers.

1.2.8.2 Modify Priority Settings

If uninterrupted, a chop saw selects either the longest or most valuable part of the cutting list to have the highest priority when production decisions are made. The prioritized part is usually included in the optimal solution unless its length is longer than the observed clear section. Once the production quota of a prioritized part has been met, attention is shifted to the item that previously had the second highest value. This sequence continues in a way that ignores parts with satisfied production requirements until all quotas are filled. There are no limits to the number of parts that can be prioritized in a chop saw cutting bill although observations from three mills indicates that up to three parts are usually prioritized at a time.

There may be times, however, when a less valuable part is cut at a rate that is limiting production or the mill immediately needs items that are in short supply. In these or other instances where conventional cutting algorithms are not fully compatible with what is needed, chop saw

operators may be able to force a part into the top priority position. However, most mill supervisors are too busy with other responsibilities and will not adjust settings unless they are seriously dissatisfied with production results.

Table 1 demonstrates an example of a chop saw cutting bill that allows users to override the prioritization process. Under normal circumstances, item number 12 would be the most sought after part as its quota has not been completely filled and it has the highest value (\$8.56) of all parts. However, a closer look at the bill reveals that item 7 has completed only 611 out its needed 7000 items while all other cutting requirements are close to completion. In table 1, the user has decided to speed up production of part number 7 by entering a 1 in its "priority of part" column. In this case, the 1 prioritizes part 7. Item number 3 has a 2 in its priority column as all 2500 of its needed parts have been cut. In this case, the 2 removes part 3 from all optimization and prioritization decisions.

Table 1. Example of A Cutting Bill.

item #	length (inch)	part price (\$)	# parts demanded	# parts cut	priority of part
1	6.5	0.14	20000	19231	0
2	26.75	1.05	7500	6210	0
3	26.75	1.44	2500	2503	2
4	32	1.88	2000	1182	0
5	36	1.54	5000	3318	0
6	36	2.12	6000	4722	0
7	49	4.47	7000	611	1
8	51	4.65	1100	892	0
9	55	5.02	2000	1017	0
10	59	5.38	1100	936	0
11	61	5.56	3500	2443	0
12	72	8.56	1800	1211	0

Table 2 shows three solutions for chop saw production results based on the cutting bill from Table 1: a 180" long usable section, and three different cutting algorithms; 1) normal cutting, 2) forcing 1 prioritized part into the solution, 3) forcing as many prioritized parts as possible into the solution. The normal solution (1) is based on trying to maximize yield of the most valuable part (eg. part 12 in Table 2). When only 1 prioritized part is forced into production (2), lumber remaining after the first part is processed according to normal optimizing procedures. Forcing as many prioritized parts as possible into the solution (3) maximizes yield of the highlighted part and only applies normal cutting procedures to whatever may be left over. According to the supervisor at the data collection mill, algorithms (1) and (3) emulate a chop saw employing unmodified and user imposed priority settings, respectively.

Table 2. Production Results From A 180" Usable Section.
(part number 7 = prioritized part, algorithm numbers in brackets)

Normal Solution (1)			Force 1 Part 7 Into Solution (2)			Force As Many Of Part 7 As Possible Into Solution (3)		
part number	part length	part price (\$)	part number	part length	part price (\$)	part number	part length	part price (\$)
6	36	2.12	7	49	4.47	4	32	1.88
12	72	8.56	10	59	5.38	7	49	4.47
12	72	8.56	12	72	8.56	7	49	4.47
						7	49	4.47
total value		\$19.24	total value		\$18.41	total value		\$15.29
total waste		0"	total waste		0"	total waste		1"

Table 2 shows that algorithm 1 or normal cutting excluded the prioritized part but achieved the highest financial value (\$19.24) of all algorithms. Algorithm 2 fit one prioritized part into its solution but ended up with a total value that was 4.5% lower than algorithm 1. Algorithm 3 cut three prioritized parts (maximum number that could fit) but accumulated a financial value that was 25.8% lower than algorithm 1 and 20.4% lower than algorithm 2. This demonstrates that user imposed restrictions to force prioritized parts can reduce total value from a board.

Based on preliminary calculations, the profitability of a mill can be improved by limiting the number of parts that are forced into a usable section of lumber. The 20.4% value difference between algorithms 2 and 3 in Table 2 is an example of what can be achieved. Under the current system, once a priority setting has been imposed, there are minimal opportunities for optimization as all efforts are put into cutting the prioritized part.

1.3 Machinery Setup

It is virtually impossible to find two secondary manufacturing plants with an identical setup as there are many factors such as customer demands and limitations of input lumber that influence operations. Determining the ideal setup for a given plant can also be difficult as market demands can change quickly once production has started. Making changes to an existing facility is often difficult due to limited resources such as plant space and money for upgraded equipment.

However, Araman (1977) showed that significant improvements in secondary manufacturing production performances can be achieved by applying minor modifications to the plant set-up. A yellow poplar mill in which full length lumber went through a planer, gang rip saw, marker station, defect saw, and automated cut to length saw, respectively, was simulated using data from an existing mill. At least 4000 board feet of interior furniture parts from No. 1 or No. 2A Common 4/4 lumber had to be produced over an eight hour shift to satisfy business obligations.

Unfortunately, only 2400 and 2200 board feet of finished parts were yielded from the higher and lower grades, respectively. The main bottleneck for both grades of lumber was the marking station

(marker and defect saw) which operated 100% of the time while the planer and gang ripsaws operated only 19 to 24% of the time.

A second set of simulation runs was done using a machinery set-up similar to the initial one but with an extra defect saw and automated cut to length saw. The new configuration fully satisfied production goals as finished parts yields of 4400 and 3900 board feet were derived from No. 1 Common and No. 2A Common grades, respectively. This example shows how simulation can be a useful tool to improve productivity and yield in a secondary manufacturing plant.

This project will examine and analyze data from algorithms having up to three different prioritized parts to find the most profitable combination. An example of an algorithm would be one that prioritizes two parts in a cutting bill and forces, if possible, one of each length into a clear section.

Questions about the transferability of project findings to potential users will, hopefully, be answered by the wide range of input variables. The range of input variables include three cutoff percentages (70%, 80%, 90% - complete) to indicate the point at which a part becomes removed from prioritization, nine different cutting bills (7 for 3" width, 2 for 3.75" width), and twenty unique priority settings rules.

Algorithms having minimal user intervention will most likely yield the highest dollar values. However, it is still necessary to do a full scale comparative analysis to objectively calculate the extent of value lost to forced cutting. Results from each data analysis will hopefully achieve the following main goals:

1. To find the cutting algorithm that achieves the highest value recovery.
2. To create a practical chop saw simulation model to test different optimization algorithms.
3. To determine, objectively, the financial benefits of using the recommended algorithm.

2.0 MATERIALS AND METHODS

2.1 Description Of The Test Mill

Conducting a project based on actual changes to the system would have been too expensive, time consuming, and restricted to a few algorithms. Therefore, the most logical choice for generating mill production data was computer simulation, an operations research technique that involves building and validating a model to represent the system. All attempts were made to minimize model assumptions by collecting large volumes of data from the project mill. Below are descriptions of the project mill, data collected, simulation development, development of algorithms, simulation procedures, and data analysis, respectively.

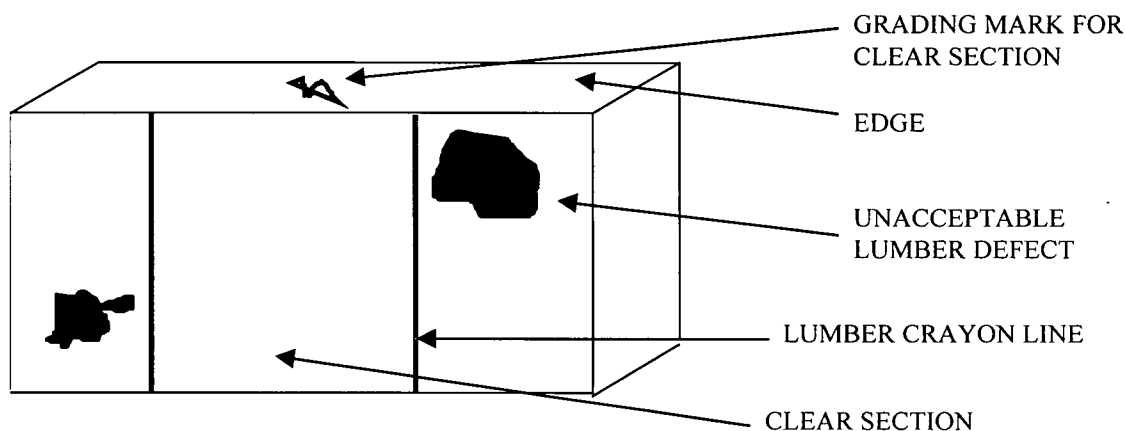
2.1.1 Mill Operation

Only basic features of the chop saw in the test mill can be described because confidentiality was a condition for collecting data. The mill studied for this project is a secondary manufacturing plant in western Canada that initially buys green lumber from sawmills. All full length lumber is kiln dried to a moisture content that is acceptable for cutting and gluing. Dried full length lumber is planed or edged, if necessary, to make its cross sectional dimensions closer to those of the parts required.

Lumber piles, each containing up to three different lengths, are positioned next to a conveyor belt that moves graded boards closer to the chop saw entrance area. Up to three graders, all responsible for the same task, can work simultaneously. Each grader isolates unacceptable defects by drawing, on the face of the board, crayon lines perpendicular to the edge. Grading

decisions are based on all four sides of a board and crayon marks on one edge indicate the grade of a usable section. Figure 3 below shows an example of the grading system.

Figure 3. Example Of Board Grading System



Boards are guided into the scanning area by rollers that apply downward pressure onto the top face. Crayon lines on the face of a board are detected by an overhead sensor that is about 2.5 inches away from the lumber surface. Profile data pertaining to the location of grading marks is collected by a side sensor or one that gets its signals from the specimen's edge. An additional light based sensor collects board length data by noting when a light beam shining across the infeed belt is blocked. Both side based sensors are about 1.5 inches away from the edge of moving lumber.

A software algorithm in the chop saw analyzes data from usable lumber sections and calculates, according to cutting bill parameters, the most valuable combination of parts that can be recovered. A set of side sensors located adjacent to the chop saw blades indicate when a board is ready for processing. One upward moving blade makes cross cuts and the board is moved forward by a conveyor belt until the next cutting location is reached.

Lumber parts are conveyed into a sorting area where six or seven automated kickers push items into their appropriate bins. Parts that do not fall into any of the categories covered by the kickers flow forward into either a waste bin for excessively short cutouts or a second conveyor area. No direct processing occurs unless a part is in very heavy demand by another station in the plant.

2.1.2 Raw Material

Of the five different dimensions (thickness and width) of full-length lumber that are processed by the participating mill, only two of them, 1.875" x 2.000" x 3.000" (3" width) and 1.875" x 3.750" (3.75" width), were studied in this project. Grades of input lumber were not disclosed by the mill. Properties of both lumber types are described below.

2.1.2.1 3" Width Lumber

Even though this kind of lumber had two possible thicknesses, 1.875" and 2.000", its width was always 3.000". Seven cutting bills, described in Table 3 below, were filled during two data collecting sessions.

Table 3. 3" Width Lumber:

cutting bill number	thickness	dates run	number of items
1	2.000	6/6/97	9
2	2.000	6/3/97	16
3	1.875	6/3/97 - 6/4/97	16
4	2.000	6/20/97 & 6/23/97	16
5	2.000	6/23/97	15
6	1.875	6/23/97 - 6/24/97	15
7	1.875	6/5/97 - 6/6/97	18

2.1.2.2 3.75" Width Lumber

Thickness and width were always 1.875" and 3.75", respectively for 3.75" Width lumber. Only two cutting bills were covered but both, as Table 4 shows, contained more parts than 3" width bills.

Table 4. 3.75" Width Lumber:

Cutting bill number	thickness	dates run	number of items
1	1.875	6/10/97 - 6/13/97	23
2	1.875	7/3/97 - 7/4/97	19

2.1.3 Products

Parts cut from full length lumber were either packaged and shipped out to customers or were laminated on-site to form products for future processing. The participating mill was very cautious about revealing exactly what was eventually created from the parts but one of the managers said that doors, ladders, cribs, and shelves were examples of end products.

For both dimensions of full-length lumber, characteristics of the parts varied significantly. Ranges of lengths and prices of 3" width lumber parts were 6.5" to 192" and \$.015 to \$19.88, respectively. Lumber parts with a 3.75" width had the same range of lengths as the of 3" width, but had a slightly smaller price range of \$.04 to \$19.15.

2.1.4 Costs

For this project, value refers to the difference between what was paid for a board and its revenue. Actual mill profits will be lower than project figures because other costs associated with parts production such as planing, handling, and drying were excluded as mill personnel considered this

information to be confidential. Therefore, using the term value/fbm was more appropriate than profit/fbm.

Again, the mill did not reveal the grades of their input lumber, so, a price per 1000 board feet of full-length lumber was obtained by averaging data from all 1995 copies of Madison's Canadian Lumber Reporter (Anonymous(1995)), a weekly publication that regularly listed two grades of 2x4 kiln dried coastal hemlock lumber, Standard/2&Better and Utility/3Common. Appendix I shows all data from both grades. After a 40% U.S. exchange rate (November 4, 1997 figure) was multiplied by the average Standard/2&Better price, a lumber cost of \$417.37/1000 fbm (Canadian) was calculated.

The main reason for applying a price or cost factor to each full-length board was to provide more realistic financial figures, as it was possible for a low grade piece, without costs, to generate a "profit" (actually revenue) of \$3.00 from part prices even though a big loss should have been incurred after lumber price was considered.

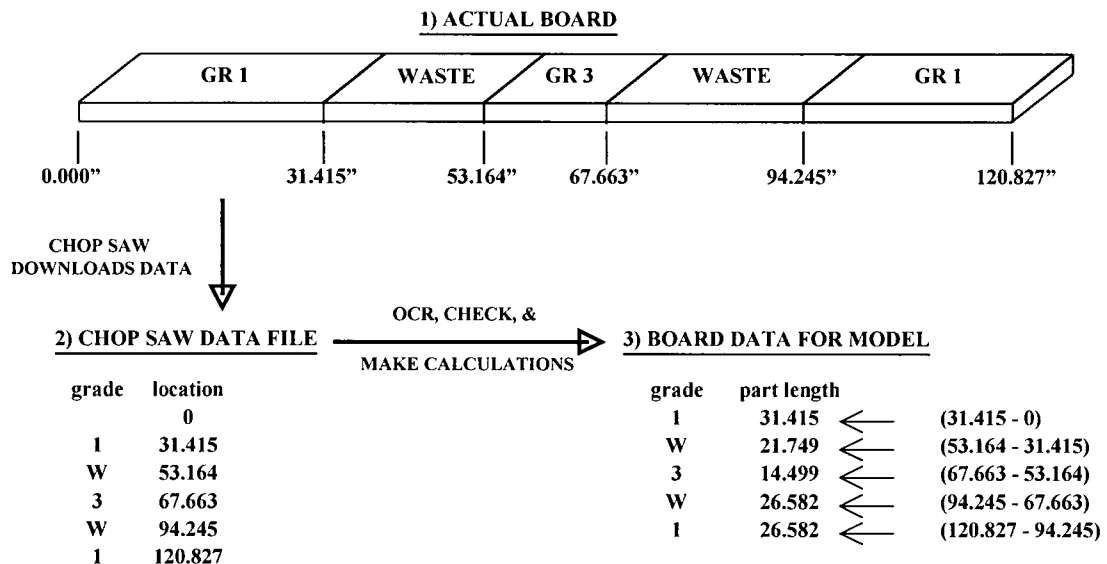
2.2 Data Collection

Most of the work in this research was non-intrusive to production. Board information was obtained from the chop saw computer and time data were collected manually. Other data were provided by mill employees. A total of four separate mill runs, each one consisting of about eight shifts or four days of production, had to be examined to collect a large enough data base.

2.2.1 Lumber Data

All full length lumber in the simulation model was from actual board data, nothing was randomly generated. Board data files, consisting of the locations of crayon marks made by the grader and total lumber length, were read into the simulation program at the beginning of a run. Figure 4 shows the steps that were taken to transform lumber crayon marks into useful model data. For each dimension of lumber, chop saw computer data files were downloaded once or twice per shift to even out the distribution of lengths collected. All information from computer files was printed out, put through optical character recognition software (converts graphics to text), checked for errors (manually and by a spreadsheet macro), and subject to calculations which derived the length of each section.

Figure 4. Steps To Acquire Lumber Data

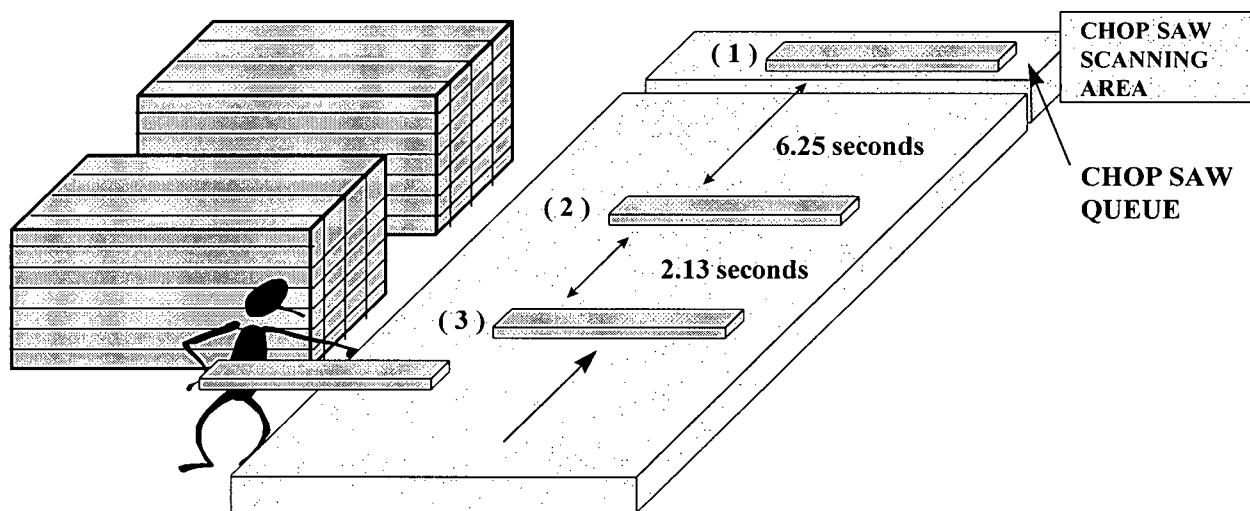


2.2.2 Time and Motion Study

None of the simulation model features could function properly unless time data were added to the graphics network. Lumber interarrival times to the chop saw queue or area where full length

lumber waited until it was ready to be scanned was gathered manually by a stop watch. Only one set of time data, from the first run, was gathered for each dimension of lumber. Figure 5 shows the grading station layout where two measurements, one for the first board and a second for the board immediately following, were taken to get one interarrival time.

Figure 5. Illustration Of Lumber Grading Station



The initial time value in Figure 5 (6.25 seconds) was based on the board 1 arriving at 0 seconds or when collection started and board 2 arriving 6.25 seconds later. At time 8.38 seconds, board 3 reached the queue, completing requirements for the second time value of 2.13 seconds.

2.2.3 Data From Mill Employees

Grading station workers wrote down when lumber packages arrived and the lengths contained within them. Extra care was taken to ensure that only information pertaining to project cutting bills was recorded as runs were often interrupted to work on different products. As was done with stop watch data, graders were only asked to record data from the first run of each dimension as the lumber population had to be consistent in data analysis.

Any changes made to chop saw priority settings during a run were recorded by mill managers on a notepad placed near the chop saw control panel. Most modifications to cutting bills involved adding and/or removing parts on a permanent or temporary basis. Fortunately, all cutting bill priorities were implemented before runs commenced and did not change during the run.

2.2.4 Yield Data

2.2.4.1 Basic Structure

Parameters from cutting bills were obtained from summary reports that were printed at the end of each run. If nothing was cut for a particular part, the item in question was not included in the simulation. Table 5 shows an example of a printed chop saw cutting bill.

Table 5. Actual Chop Saw Cutting Bill

Item = item number
Length = part length (inches)
Req. = number of parts required
Cut = number of parts actually cut
Rest = number of parts remaining to be cut
Pr. = priority setting (2 = finished, 1 = prioritized)
price = price per part
price/MBF = price (\$) per 1000 board feet
fact = cut factor (not used in project)
kicker = kicker number

GRADE 1									
Item	Length	Req.	Cut	Rest	Pr	Price	price/MBF	fact	kicker
1	24.803	1000	0	1000	2	1.570	1519.2	1.00	6
2	36.000	5000	63	4937	0	1.870	1246.7	1.05	3
3	48.425	1500	90	1410	0	3.060	1516.6	1.10	6
4	60.236	1500	95	1405	0	3.800	1514.0	1.15	7
5	72.047	1500	100	1400	0	4.550	1515.7	1.20	7
6	96.000	500	51	449	0	6.500	1625.0	1.25	0
7	120.000	1100	0	1100	2	12.420	2484.0	1.30	0
8	144.000	3250	8	3242	1	14.910	2485.0	1.35	0
9	168.000	250	0	250	1	17.390	2484.3	1.45	0
10	192.000	500	0	500	1	19.880	2485.0	1.50	0
GRADE 2									
Item	Length	Req.	Cut	Rest	Pr	Price	price/MBF	fact	kicker
1	36.000	2500	203	2297	0	1.870	1246.7	0.85	3
2	96.000	1500	18	1482	0	5.200	1300.0	0.86	0
3	120.000	500	59	441	0	12.410	2482.0	0.87	0
4	144.000	1500	28	1472	1	14.890	2481.7	0.88	0
5	168.000	250	0	250	0	17.370	2481.4	0.89	0
6	192.000	250	0	250	0	19.880	2485.0	0.90	0
GRADE 3									

Item	Length	Req.	Cut	Rest	Pr	Price	price/MBF	fact	kicker
1	6.500	10000	140	9860	0	0.140	516.9	0.50	1
2	36.000	2500	467	2033	0	1.480	986.7	0.75	5
GRADE 4									
Item	Length	Req.	Cut	Rest	Pr	Price	price/MBF	fact	kicker
1	35.000	250	22	228	0	0.025	17.1	0.50	7
2	84.000	250	2	248	0	0.070	20.0	0.75	7

2.2.4.2 Modifications To Demand

A preset demand was provided by each cutting bill, however, part quotas were rarely filled and no consistent completion percentage existed. Mill personnel said that taking exactly what was requested by customers and entering it into the cutting bill was not always done as some parts could be overproduced without being a burden on inventory levels. If a part with a high grade was long enough to be reprocessed into another usable item, then no limits were necessary.

Another reason for large demand figures was that if a particular part was required by three or four cutting bills, demand for the entire run was used, not the individual cutting bill. The mill also sometimes judged demand for a part by entering a large number and stopping production after inventory levels were examined or if the manager felt that the next run could easily fill the void.

As expected, the subjective nature of the mill's techniques for deriving demand made them nontransferable to project work. However, attempts still had to be made to estimate actual demand to make simulated data comparable to those from the mill. Below are descriptions of the three attempts that were made to find suitable demand levels for each cutting bill.

2.2.4.2.1 Actual Cut

Basing cutting bill demand on what was actually cut resulted in lumber recovery figures that were almost identical to actual data from the mills. Table 6 shows how demand data in the simulation model cutting bill (B) was transferred from a mill printout (A).

Table 6. "Actual Cut" Cutting Bill Demand

(A) = Cutting Bill Downloaded From Chop Saw, (B) = Cutting Bill From Chop Saw Model

GRADE 2									
Item	Length	Req.	Cut	Rest	Pr	Price	Price/MBF	Fact.	Kicker
1	36.000	2500	203	2297	0	1.870	1246.7	0.85	3
2	96.000	1500	18	1482	0	5.200	1300.0	0.86	0
3	120.000	500	59	441	0	12.410	2482.0	0.87	0
:	:	:	:	:	:	:	:	:	:

Grade	Length	Kicker	Req.	Cut	Price	Pr
2	36	3	203	0	1.870	0
2	96	0	18	0	5.200	0
2	120	0	59	0	12.410	0
:	:	:	:	:	:	:

Expectations of deriving financial and yield results resembling actual data were rarely met as the priority settings formula did not give attention, until later in a run, to parts which were highly valued but had low demand levels. Consequently, large volumes of long usable lumber were cut into shorter parts and the simulation runs ended up being much longer than they should have been.

2.2.4.2.2 Actual Demand

A second approach was taken to see if emulating mill results was possible or worthwhile. Using three 3" width cutting bills with demand from mill runs, trials using mill settings (2 or 3 parts that were prioritized by the mill) were done by tripling the prices of prioritized parts. Each run

was stopped once simulated time equaled the duration of the actual run. Multiple printouts of all cutting bills confirmed that prioritized parts selected by mill personnel at the beginning of a run did not change.

Again, failure was encountered when comparisons were made with actual data. Slight improvements were seen in contrasts between highly valued parts but differences between other items were so large that conducting statistical tests for significance would have been a waste of time.

2.2.4.2.3 Pseudo Demand

With little or no chances of the project programs being able to reproduce exactly what was done by the mill, the only alternative was to create a “pseudo” demand to be used for comparing performance of the algorithms. With pseudo demand, no direct comparisons could be made with actual data, however, practicality and consistency were improved.

Pseudo demand was formulated in a way that transformed what was actually cut into a format that was not only more compatible with the priority settings formula but was also similar to, but less than, actual demand. Below are the rules for creating pseudo demand:

- For each cutting bill item, if the actual number of parts cut is less than 10, demand equals 10, otherwise, multiply actual number of parts cut by 1.5:
- Result from above are then categorized according to the following format:
 - If (actual cut)*1.5 \leq 10, demand = 10
 - If (actual cut)*1.5 $<$ 100, demand rounded to upper 10th increment.
 - If (actual cut)*1.5 \geq 100, demand rounded to upper 10th increment.
 - If (actual cut)*1.5 \geq 1000, demand rounded to upper 100th increment.

Table 7 below shows an example of how number of parts cut data from an actual chop saw run cutting bill (A) was converted to demand or number of parts needed for a simulation model cutting bill (B).

Table 7. Pseudo Demand Example.

(A) Number Of Parts Cut	(B) Demand
679	1100
29	50
285	430
212	320
178	270
3	10
32	50
39	60
37	60

Appendix II shows all cutting bills that were employed in the project.

2.3 Development Of Chop Saw Algorithms

Cutting algorithms used the priority settings to govern how parts were cut from a section of lumber. An example of a cutting algorithm using one item would be one that forced as many prioritized parts as possible into a section and cut remaining lumber according to normal optimization. A total of 20 algorithms (Table 8) were tested during the project.

Table 8. Cutting Algorithms

Algorithm #	# Prioritized Parts ¹	# Forced In	Cutoff % ²
1	1	1	70
2	1	1	80
3	1	1	90
4	1	UNLIMITED	70
5	1	UNLIMITED	80
6	1	UNLIMITED	90
7	2	1 OF EACH	70
8	2	1 OF EACH	80
9	2	1 OF EACH	90
10	2	2 OF EACH	70
11	2	2 OF EACH	80
12	2	2 OF EACH	90
13	3	1 OF EACH	70
14	3	1 OF EACH	80
15	3	1 OF EACH	90
16	3	2 OF EACH	70
17	3	2 OF EACH	80
18	3	2 OF EACH	90
19	MILL SETTINGS	NA	NA
20	NO PRIORITY SETTINGS	NA	NA

1 = Part(s) were prioritized according to remaining value or
(number of parts needed - number of parts cut)*price per part

2 = A part became ineligible for prioritization once a certain percentage of its demand was satisfied.

C programs emulating algorithm 19, mill settings, only considered the 2 to 4 items that had been given preference in the real run. No new parts were prioritized once the initially emphasized ones were completed. Selection of parts was done by part value, not remaining value.

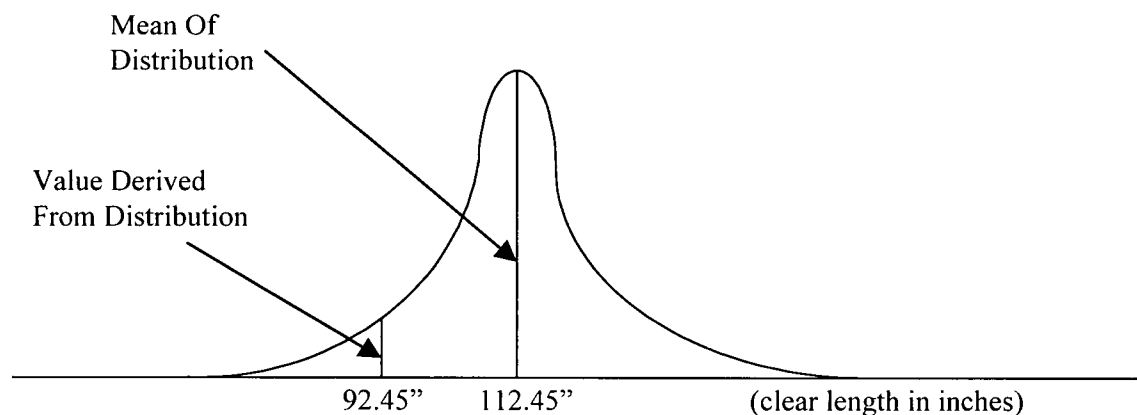
2.4 Simulation Procedures

Simulation can be either continuous or discrete, the former having one or more sections of the model changing continuously over time while changes only occur in the latter at a discrete set of time points. For this thesis project, only properties and rules of discrete simulation was considered as events commonplace in lumber processing such as lumber arriving at a rip saw happen at exact points in time.

It must be noted here that simulation programs included in automated chop saw software are different from discrete simulation. Chop saw software uses deterministic simulation or event generation based on board data downloaded from previous mill runs. There is no randomness in deterministic simulation - a typical run would apply a new set of cutting rules to clear section values from a previous run.

Discrete simulation creates events or numerical values by combining random numbers with statistical parameters from previous mill runs. Data collected from an actual event are analyzed to get the distribution and any relevant statistical values. Figure 6 shows graphically how discrete simulation has derived a board length of 92.45" by taking a random number and applying it to a normal distribution with a mean of 112.45".

Figure 6. Discrete Simulation Example Using Normal Distribution



Discrete simulation also allows direct or unbiased comparisons between two different algorithms if the seeds or starting points of the random numbers are consistent in all runs.

2.4.1 Graphical Elements Of The Chop Saw Simulation Model

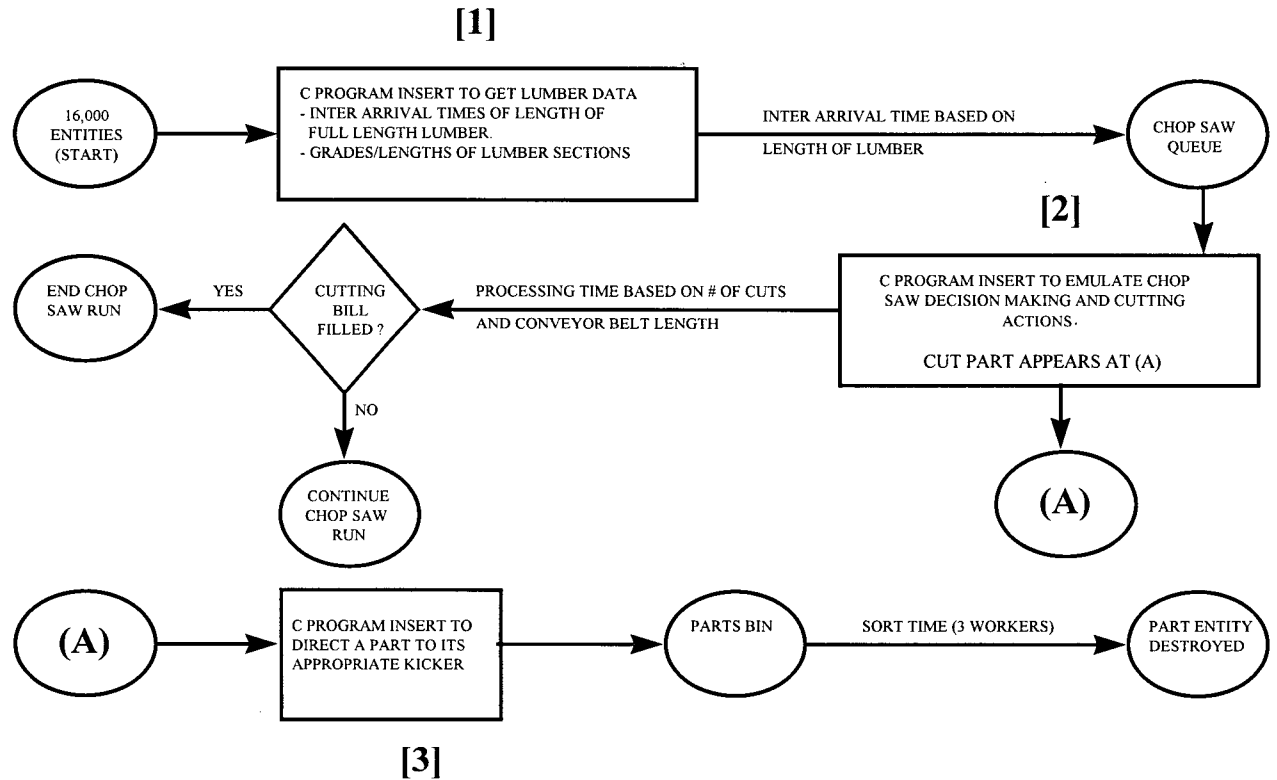
All simulation work was done using Awesim, a software package that enables users to create models graphically with icons that represent common simulation elements such as queues and entity paths. Program modules can be inserted into models when necessary. For this project, each simulation run had a distinct set of program inserts (written in C) but the same graphical model was used in all runs or replications.

It should be made clear that the term “graphical” did not necessarily mean “animation” as the former refers to a windows interface work area that simplified model development by allowing users to “drag and drop” icons. Graphical models were needed regardless of the model output and consisted of two sections, lumber movement and downtime.

2.4.1.1 Lumber Movement

Figure 7 shows the network that facilitated lumber entity flow with the help of more complicated C program inserts, symbolized by rectangular boxes. At the beginning of a run, 16,000 entities representing full length lumber were put into a queue from which boards were selected, assigned characteristics, and forwarded to another waiting area where they remained until the chop saw was ready for cutting. Each time a lumber part was cut, a new entity was created, added to the network at point (A) in Figure 7, and tallied.

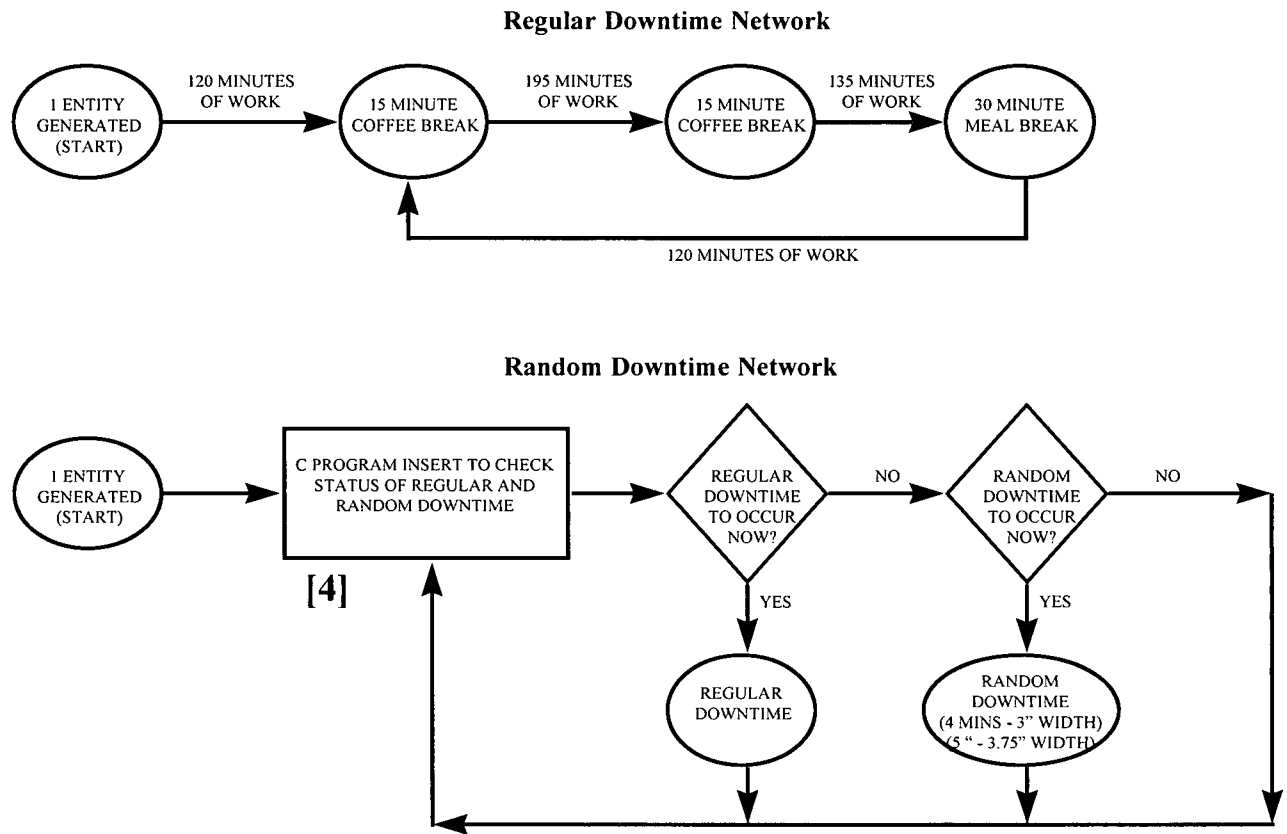
Figure 7. Full Length Lumber and Parts Flow Networks.



2.4.1.2 Downtime

Also present in the graphical model were networks to add downtime or times during a run when mill machinery was not operating. Both forms of industrial downtime, regular (shift change, coffee/meal breaks) and random (in which work was halted due to unexpected factors such as mechanical failures) were managed by networks in Figure 8.

Figure 8. Downtime Networks



Using the equation below, 4.4 (4) and 4.95 (5) minutes of random downtime per hour were calculated for 3" width and 3.75" width lumber, respectively.

$$\text{random downtime per hour} = \text{runtime} - \text{work time} - \text{waiting time} \quad [\text{Equation 1}]$$

where:

runtime = length of the work shift (minutes).

work time = time spent by chop saw on cutting, scanning, and optimizing (minutes).

waiting time = time spent by chop saw waiting for full length lumber (minutes).

Although equation 1 is a fixed figure, it is referred to as "random" as it occurs at randomly (uniform distribution) selected points within each hour of simulated time. Data pertaining to run time and work time were copied from reports that were printed either at the end of a shift or when work had to be done on a new cutting bill. Each observation in the calculation of average

random downtime per hour came from one shift/run report. Many evening shift totals were lost as the chop saw computer clock reset at midnight. Overall, twenty production intervals were successfully recorded and appear in Appendix III.

Waiting time or time spent by the chop saw waiting for full length lumber was the result of combining time data with some very subjective assumptions. For both lumber dimensions, two assumptions were made for waiting downtime; boards entered the scanning area every two seconds as queue sizes of zero were seen often and 250 boards were processed each hour. An average of 8.33 minutes $((2/60)*250)$ of waiting downtime occurred each hour.

2.4.2 C Program Inserts Of Chop Saw Simulation Model

Figures 7 and 8 show only four stations at which C programs were called upon to process lumber or check downtime. Program [3] in Figure 7 (kicker) and [4] in Figure 8 (downtime) were easy to implement. However, the other two, assigning lumber data ([2] in Figure 7) and cutting lumber parts ([3] in Figure 7), were much more complex. Below are descriptions of functions that assigned lumber data and made cutting decisions, respectively.

2.4.2.1 Assigning Lumber Data

In actual production, lumber was carried by a forklift to a grading area where boards were handled and assigned grades by one or two graders before they were conveyed to the chop saw queue. One grader was present most of the time as a second grader usually was not added unless previously cut lumber was re entered into the grading area.

For the model, only one grader was used at all times and lumber properties were not assigned to entities until they were released or selected from the initial lumber queue. Table 9 below shows all the steps taken to give entities all the information they needed to mirror actual lumber.

Table 9. C Program Steps To Obtain Lumber Information

- 1) Get Board Number (eg. 3)
- 2) Get Board Selection Information (eg. choose board between #'s 201 and 300, 10' length)
- 3) Select Board (eg. select board # 207 and get all section information)
- 4) Get Interarrival Time (eg. based on 10' length and random #, 5 seconds)

2.4.2.1.1 Get Board Number/Selection Information

After selection, an entity was given a board number equal to the total number of processed boards plus one. A data file designated two interval numbers (for selecting board properties) and an integer length (for interarrival time selection) to the entity according to its board number. An example of data assignment is shown in Table 10 where a 3.75" width entity having a board number of 3 receives interval values of 201 and 300 or the interval covering 10' long lumber.

Table 10. Sample Of Lumber Identification File

board #	board selection interval (first)	board selection interval (second)	assigned length in feet
1 - 96	201	300	10
97 - 167	101	200	9
168 - 238	1	100	8
....

Data in the lumber identification file was provided by grading station workers who, as was mentioned earlier, wrote down lumber package information. As Table 9 shows, the sequence of lumber arrivals, not their times, were transferred to the simulation model.

All packages always consisted of 238 pieces, however, getting accurate length tallies was impossible as random or inconsistent length distributions were always present. Numerous packages in the storage yard were examined to help make reasonable assumptions about length data. If three different lengths were enclosed in a package, for example, 96 boards or 40.336% of the contents were of the longest length and leftover stock was split equally among the other two lengths. Table 11 shows a complete list of the package composition rules for both dimensions.

Table 11. Lumber Package Length Composition Rules
(Applies To Both Dimensions, Rank - 1 = Longest Length)

Length/Package	Rank	# Boards	Percentage
2	1	119	50.000 %
	2	119	50.000 %
3	1	96	40.336 %
	2	71	29.832 %
	3	71	29.832 %
4	1	71	29.832 %
	2	71	29.832 %
	3	48	20.168 %
	4	48	20.168 %
5	1	54	22.689 %
	2	54	22.689 %
	3	54	22.689 %
	4	38	15.966 %
	5	38	15.966 %

2.4.2.1.2 Select Board

A uniformly distributed random number, limited by the entity's two interval values (eg. 201 and 300 from the previous step), was drawn. A large board data file consisting of information from about 1300 full length boards or 100 for each length (8' to 20') was scanned until the row having a value equal to the random number was located. More boards could have been added to the information base but some of the mill's lumber lengths (such as 18 footers) were not cut regularly. Each row in the file was created from actual chop saw computer data and consisted of grades and lengths of all sections, usable or waste, from one particular board.

For demonstrative purposes, an example is shown below where random number 207 is chosen.

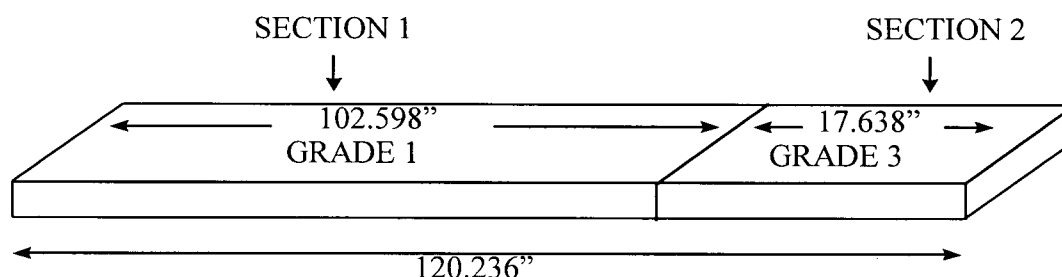
Table 12 shows the resulting information taken from the board data file in which the selected board characteristics appear on line 207 (bold font).

Table 12. Example Of Board Data File.

#	board length (inches)	number of sections	section 1 length (in.)	section 1 grade	section 2 length (in.)	section 2 grade	section 3 length (in.)	section 3 grade
....
205	120.157	3	69.646	3	2.283	17	48.228	1
206	120.236	1	120.236	1	0	0	0	0
207	120.236	2	102.598	1	17.638	3	0	0
....

Figure 9 shows the 3 dimensional view of the board selected at row 207 of the data file.

Figure 9. Diagram Of Board From Row 207 In Table 12



Sampling with replacement, a technique which selected a board from a batch and returned it for possible reselection, was the sampling method used. For example, a 96.215" board chosen from 100 other boards having similar lengths could have been the very next sample or never been selected again. Alternatively, new boards could have been created by generating sections (grade/waste) from statistical distributions and summing them until the full length of the sample was reached. Despite its higher level of randomness, generating new boards was abandoned as too much time would have been required to accommodate all the different lengths.

2.4.2.1.3 Select Interarrival Time

An entity could not advance until it was granted an interarrival time (time between lumber arrivals) to the chop saw queue. A C program function drew a uniformly distributed random number between 0 and 1 which helped get the entity's length based interarrival time from a cumulative frequency distribution. Using Table 13 below, if a random number of .72 was drawn and the frequency distribution for 10' lumber (10 - integer length from the example) was utilized, the entity's interarrival time would be 9 seconds.

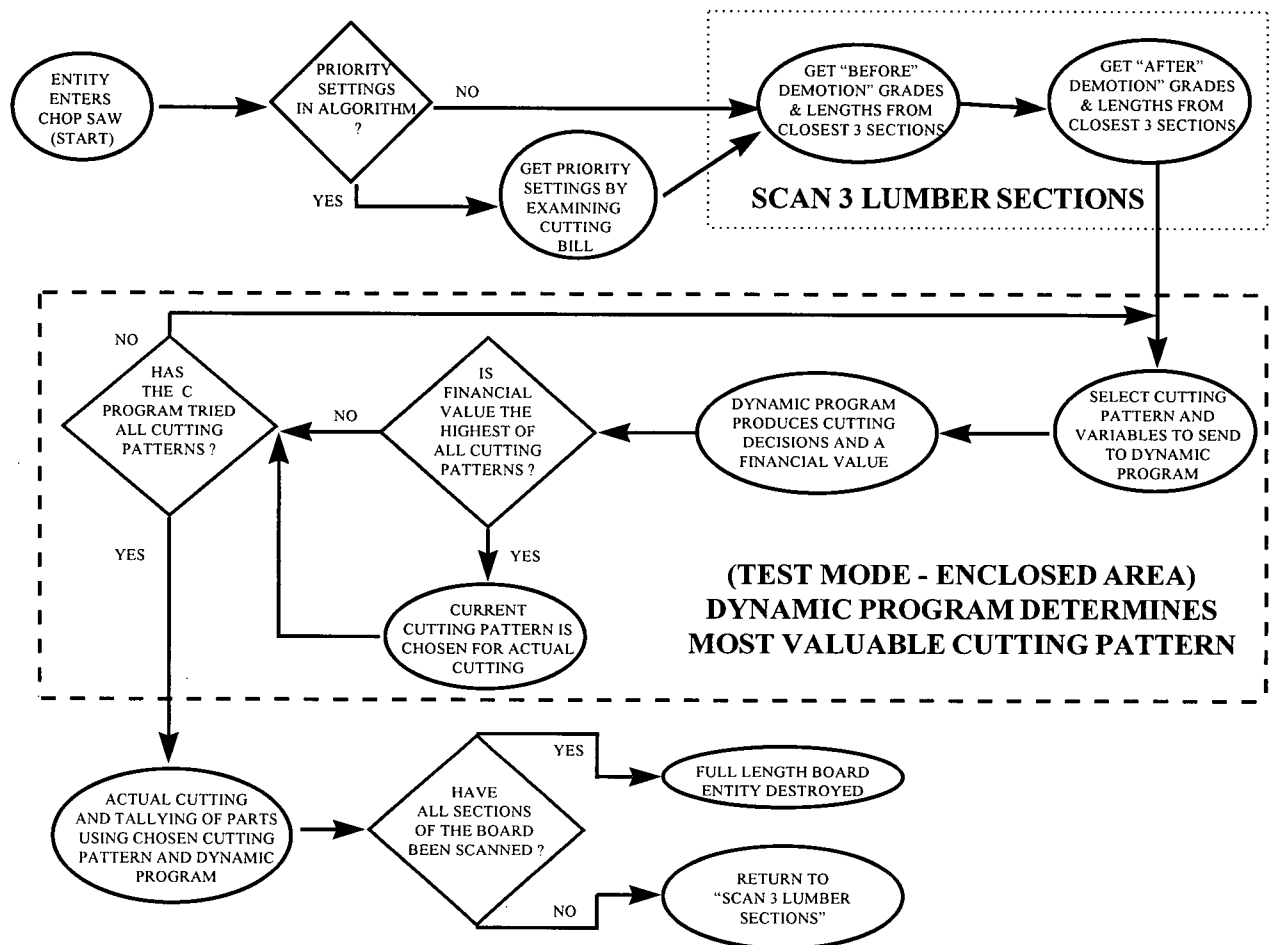
Table 13. Cumulative Distribution Of Interarrival Times For 10' Lumber

interarrival time (seconds)	interval
5	0.066265
6	0.216867
7	0.228916
8	0.710843
9	0.740964
10	0.746988
11	0.921687
13	0.951807
14	0.96988
16	0.993976
18	1

2.4.2.2 Making Cutting Decisions

Once a lumber entity entered the chop saw, procedures shown in Figure 10 transformed lumber sections into parts. Detailed descriptions of points in the network follow:

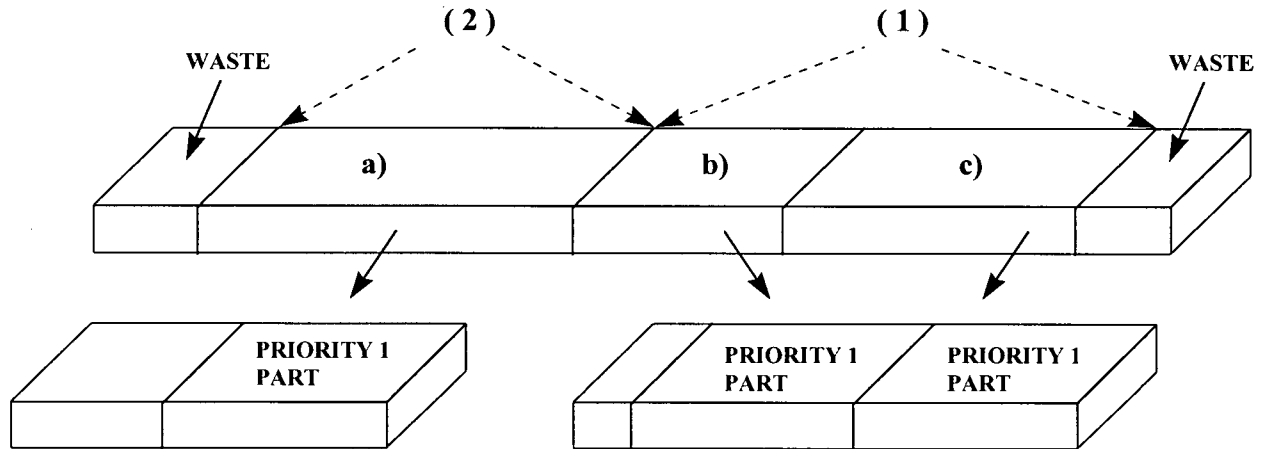
Figure 10. Flowchart Of Procedures For Cutting Parts From Full Length Lumber



The terms “cutting algorithm” and “pattern” are explained here to prevent further confusion. Figure 11 shows how a board was cut with a pattern that created two sections from three by combining sections b) and c) and used a cutting algorithm that forced in as many priority 1 parts as possible.

Figure 11. Cutting Algorithm and Cutting Pattern

(cutting pattern - initial sections = a), b), and c), final sections = (1), (2))



2.4.2.2.1 Get Cutting Bill Priority Settings

Each time a full length board entered the chop saw, scanning of the cutting bill was done to get identities of part(s) to be forced into the combination of parts removed from a section. Also known as priority settings, forced parts were based on highest remaining value or:

$$\text{remaining value} = (\text{number of parts needed} - \text{number of parts cut}) * \text{price of part} \quad [\text{Equation 2}]$$

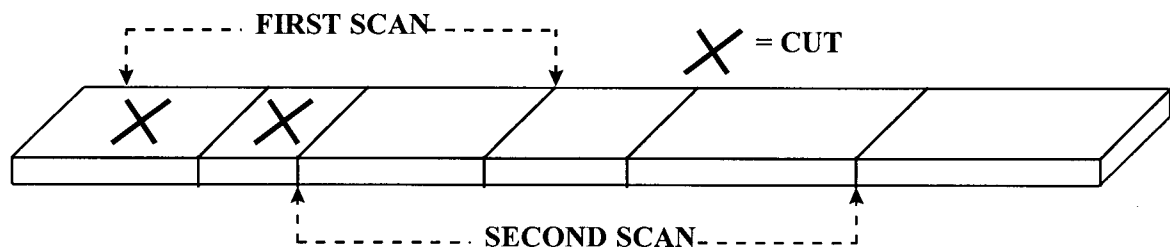
Cross sectional dimensions of the parts in question were constant, hence, they were not included in equation 2. If only one grade is present in a cutting bill, formulas based on length are fine but up to four different grades of lumber were cut during a mill run. Part length was therefore excluded as it was possible for a long part with low value to override a shorter but more valuable item.

Previously published length based formulas include $\text{Priority} = \text{Length}^2 * \text{Width}$ (from Wodzinski and Hahm; (1966)), $\text{Priority} = \text{Length}^{\text{Weight}} * \text{Width}$ (from Maristany *et al.* (1990)), and $\text{Length}^2 * \text{Width}^2$ (from Steele and Gazo (1995)). Thomas (1996) introduced weighting factors (WF) with a $\text{Priority} = \text{Length}^{\text{WF}_{\text{Length}}} * \text{Width}^{\text{WF}_{\text{Width}}}$ formula. Biases relating to parts quantities which existed in older priority formulas were overcome by WFs but part value was still being ignored. A complete description of how priority settings were utilized in cutting algorithms is explained in the subsequent “Development Of Algorithms” section.

2.4.2.2.2 Get The Best Cutting Pattern

Up to three consecutive lumber sections were scanned before a series of tests determined the most valuable cutting pattern or sequence by which sections were cut. Actual cutting was applied to the most profitable pattern after all possibilities had been tested. Figure 12 shows an example of scanning where the remaining third section of the first scan became the first section of the second scan.

Figure 12. Example Of Board Scanning.



Depending on the grades present or number of sections, up to 14 possible cutting patterns were examined by the test mode section of the program (area enclosed by a dotted line in Figure 10). Demotion of a grade occurred if a section was not long enough to meet grading standards. Figure 13 shows diagrams of all the patterns.

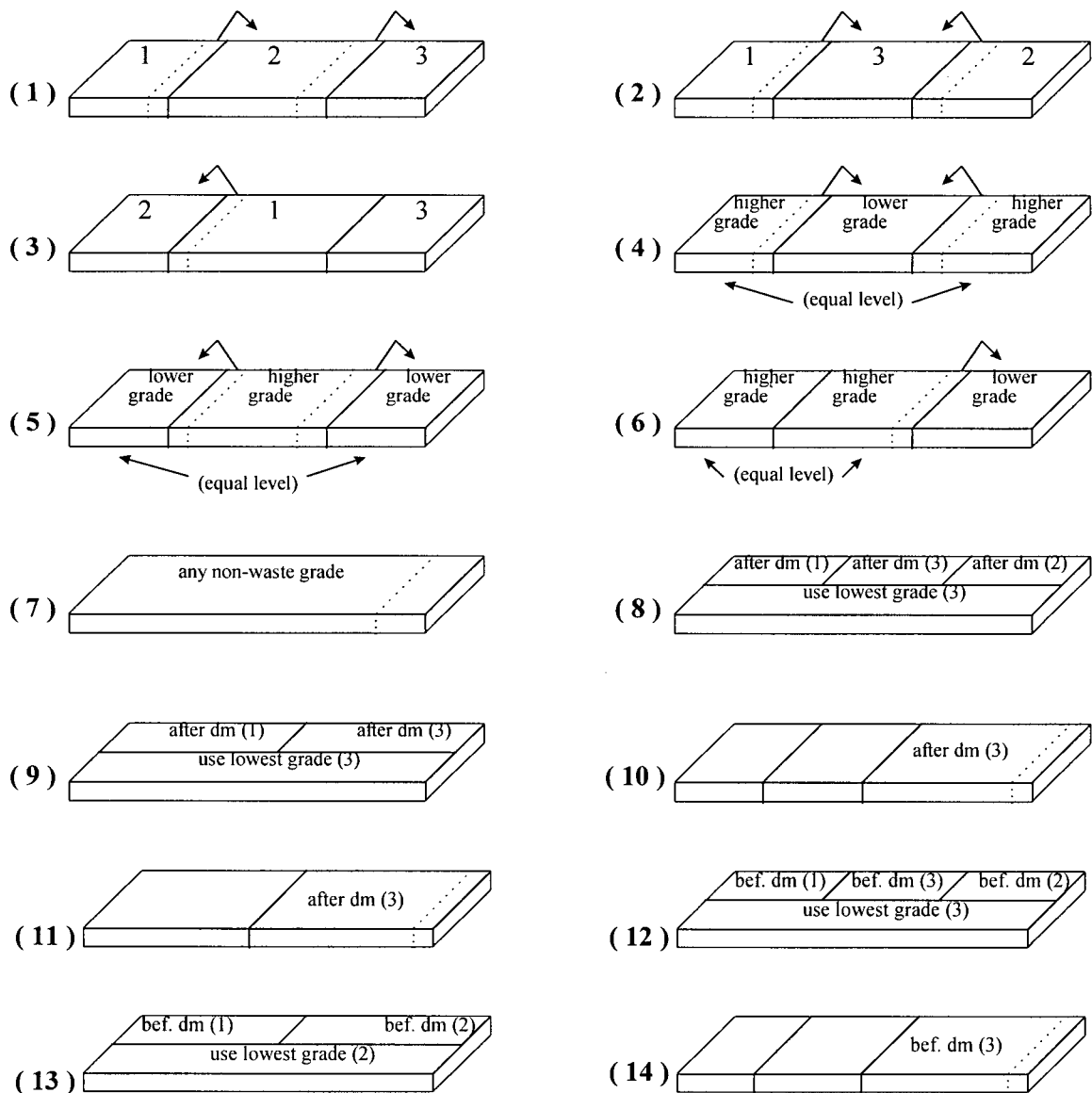
Figure 13. Cutting Patterns For Test Mode

1 = highest grade, 2 = 2nd highest grade, 3 = lowest grade, dm = demotion, bef. = before
 blank sections = if value from nonblank sections are best, cut blank sections only
 (all grades based on after demotion results unless specified)

example of explanation:

pattern (2):

- Cut parts from the section having the highest grade and add its remainder to the section having the lowest grade.
- Cut parts from the section having the second highest grade and add its remainder to the section having the lowest grade.
- Cut parts from the section with having the lowest grade - remainder is waste.



2.4.2.2.3 Dynamic Program

As was shown earlier, the chop saw program obtained, through a series of trial runs, the most valuable cutting pattern before any actual cutting commenced. Even though trial runs and actual cutting used the same dynamic program, outputs from each cutting mode were treated differently.

In actual cutting, tallied parts were incorporated into the cutting bill and remaining lumber was retained for further use or discarded. Trial runs had no influence on the cutting bill and returned a dollar value that was kept for comparisons with other cutting patterns.

2.4.2.2.3.1 Features Common To Both Cutting Modes

2.4.2.2.3.1.1 Accuracy

Three levels of cutting accuracy (1", 1/5", and 1 mm) were thoroughly tested to find the one that best satisfied the criteria of relatively quick processing time and minimal number of errors or incorrect cutting decisions due to measuring units which were incompatible with part lengths. No errors were found with 1 mm accuracy, however, it took an hour to complete a mere 857 minutes of simulated time. Run times were significantly shorter with 1" accuracy but errors were common even after adjustments were made. One fifths of an inch accuracy or about 5.08 mm was chosen because of its compatibility with most of the cutting bill parts and respectable run execution time of one hour to 5400 minutes of simulated time.

2.4.2.2.3.1.2 Fingerjointing

Waste from parts production was minimized by fingerjointing, a feature of the dynamic program that examined leftover lumber and made a length based decision to either call it waste or stock

that could be used later to create laminated lumber. If higher value was achievable, usable lumber was cut to fingerjointing stock instead of cutting bill parts.

Rules for fingerjointing varied between cutting bills and were contained in small data files which were imported into the C program before any simulation work started. Table 14 below shows an example of fingerjointing rules and Appendix IV shows rules from all nine cutting bills (7 - 3" width, 2 - 3.75" width).

Table 14. Example Of Fingerjoint Rules (3" Width - Cutbill #6)

grade	min. length	\$/inch of length	kicker
1	8	0.04	2
2	8	0.02	2
3	10	0.015	4

2.4.2.2.3.1.3 Cutting Considerations

Parts and leftover lumber were not the only components of a board. Small amounts of wood removed by a saw blade or kerf also had to be incorporated into cutting calculations. All mill runs used a kerf value of .197" (5 mm); therefore the same constant was implemented in project models. After a cutting bill or fingerjoint part was cut, kerf was always subtracted from remaining lumber before any subsequent work commenced. Even though it was possible to get two parts from one section, kerf was applied to all parts as the one additional cut compensated for any end trim requirements. For lead trim (kerf applied to the front end of a board before scanning) a value of .187" was always used.

2.4.2.2.3.2 Features Applicable Only To Actual Cutting

2.4.2.2.3.2.1 Statistics From Each Board

In addition to influencing the cutting bill, actual cutting added data to the array that kept track of yield from each board. Each time a part was cut, selected information was recorded to an array cell (named according to the board number - eg. board[2][x]) which was later used for generating post-run reports. Examples of summary reports and board data files from a simulation run are shown in Tables 15 and 16, respectively:

Table 15. Example Of Simulation Run Summary Report

1	cutting bill
2	thickness
3	width
955	completed boards
957	boards in system
211.31	mins completion time
0.56	\$/fbm (overall)
22.94	linear inches (average waste/board)
85016	inches (total lin.parts cut)
50.94	pct rec(parts)
59980.06	inches (total lin. fj cut)
35.94	pct rec(fj)
166905.50	inches (total lin.overall)
86.87	pct rec(total)
3924.78	\$ total value -1 from completed boards
6968.99	\$ total value -2 from kickers
891	boards were profitable
64	boards lost money
63	clears (inactivity)
0	clears (shorts)
63	clears total

number of 20 ft. clear boards for inactivity = 63
percent of 20 ft. clear boards for inactivity = 6.597
number of 20 ft. clear boards for inadequate length = 0
percent of 20 ft. clear boards for inadequate length = 0
random # = 1, cutoff pct= 0.70, algorithm = 1a

Table 16. Example Of Board Data File

(total\$ = total value from board, partslen = total length of parts cut, fflen = total length of fingerjoint stock cut, fintime = time when board completed)

#	length	total\$	waste	partslen	fflen	fintime	cost
1	168.622	0.1403	57.43	90.5	20.69	0.29	2.93
2	168.346	2.9484	19.2	121	28.15	0.47	2.93
3	168.543	2.0347	30.26	85	53.28	0.61	2.93
4	170.039	12.613	2.04	168	0	0.84	2.96
5	168.583	4.5566	9.12	108	51.46	1.11	2.93
:	:	:	:	:	:	:	:

2.4.2.2.3.2 Kicker

After cutting and information collecting, parts were directed to a kicker at which they were tallied. Use of kickers was implemented primarily for animated models as the cutting bill provided enough useful data for model users.

2.4.2.2.3.3 Intervention

Modifying priority settings on a regular basis was not the only aspect of the model where automated intervention was allowed to override natural cutting. When testing of the chop saw simulation model was done, it was revealed that there were times when input lumber lengths were less than the shortest part required by the cutting bill. Another weakness with the initial model was the tendency for the chop saw to run for long periods of time without producing a cutting bill part.

Printouts of test runs showed that when nearing completion, the chop saw cutting bill sometimes went unchanged for up to 40 minutes even if input lumber was longer than the required parts. Under no circumstances would any secondary manufacturing plant tolerate excessive production of fingerjoint grade parts.

When faced with poor production results of any kind, mill managers have two relatively economically feasible options of enhancing yields of scarce stock; certain cutting bill parts can be removed and/or priority settings can be adjusted to emphasize needed parts. A last resort method is to introduce long high grade lumber into the chop saw run, a practice that fills parts quotas but increases costs. For the project model, adding clear lumber when it was appropriate was the only logical choice as removing parts from the cutting bill was too subjective for C programs and priority settings were closely monitored by the model.

Functions that constantly kept track of production activities added 20' grade 1 or clear lumber if the chop saw went 5 minutes without adding items to the cutting bill or if lumber at the grading station was too short for creating non-fingerjoint parts. When mill workers were asked about when they added long or clear lumber, they had trouble giving definite answers as many circumstantial factors go into such a decision. A five minute inactivity period was chosen and found to be relatively non-dictative of production.

A premium or penalty multiplication factor of 1.50 to increase the cost of 20' clear lumber was calculated by taking the average of ratios based on dividing lower grade prices into higher ones or:

$$\text{penalty for using 20' clears} = [\text{Standard}/\#2\&\text{Better price}(\$)]/[\text{Utility}/\#3\text{Common price}(\$)]$$

[Equation 3]

Each 20' clear; therefore, cost the mill \$5.87 instead of \$3.91. Without higher costs for long clears, it would have been impossible to distinguish between the value recovery results of poorly and well performing algorithms.

2.5 Data Analysis

2.5.1 Analysis Variables

2.5.1.1 Value Recovery Per Fbm

The main goal was to find an algorithm which yielded the best performance results in terms of value recovery or profits per board footage (value/fbm), a variable that encompassed both the economical and productive aspects of sawmilling. Foot board measure¹ or fbm is a commonly used forestry industry term to present lumber volume. Value recovery per fbm was calculated by the formula:

$$\text{value per fbm} = \frac{\text{total profit from all parts}(\$)}{\text{total fbm of input lumber}} \quad [\text{equation 4}]$$

As an example, if a total of 178212.2 linear inches of lumber was processed during a 3.75" width run, its volume equivalency was 8701.77 fbm or:

$$\begin{aligned} \text{thickness} &= 47.625 \text{ mm (1.875 inches)} \\ \text{width} &= 3.75 \text{ inches} \\ \text{length} &= 178212.2 \text{ inches} \\ \\ \text{fbm} &= ((1.875 * 3.75) / 12) * (178212.2 / 12) \\ &= 8701.77 \end{aligned}$$

Assuming that the total value from all parts from a board equaled \$6362.91 then:

$$\text{value per fbm} = \frac{\$6362.91}{8701.77 \text{ fbm}} = \frac{.7312}{\text{fbm}}$$

Algorithm averages, each one consisting of 21 observations (3 replications X 7 cutting bills), from three other simulation run variables (number of 20' clears, number of boards processed, and

¹ One foot board measure is equal to 1' x 12" x 1" of lumber

percent recovery of parts) were examined to ensure that high value/fbm figures were not obtained at the expense of other production factors. Furthermore, analysis of the three external variables was necessary to see if cutting algorithm was the only factor that determined value/fbm results.

2.5.1.2 Number Of 20' Clears Added

One of the most powerful influences on a chop saw run is the option of adding long, clear full length lumber when parts are cut at an unacceptable rate. If high quality stock is used as a corrective factor, caution has to be taken as it is possible for the worst chop saw setup to produce respectable results if large volumes of clears have been implemented. Analysis of the average number of grade 1 - 20' clears used by each cutting algorithm was therefore necessary to reveal if any biases were present.

2.5.1.3 Percent Recovery Of Parts

The ability of a chop saw to complete an order with minimal waste and fingerjoint stock was measured by its parts recovery or the percentage of input lumber that contributed to producing cutting bill parts. Formulated as:

$$\% \text{ Parts Recovery} = \frac{\text{Total Linear Length Of Parts Produced(inches)}}{\text{Total Linear Length(inches)}} \quad [\text{equation 5}]$$

Linear length was used instead of fbm because all full length lumber in a run had the same cross sectional dimensions. Fingerjoint graded parts were excluded from the equation as their presence inflated recovery percentages, especially if all grades of lumber could be salvaged.

2.5.1.4 Number Of Boards Processed

Secondary manufacturing mills are often under pressure from their customers to complete orders by specified dates. Meeting deadlines can be difficult due to the heterogeneous nature of full length lumber and the lack of available information about how chop saws work. Mills encountering chronic problems with run times would probably be interested in a cutting algorithm that completes a cutting bill with the least amount of input lumber.

It can be said with confidence that normal run conditions were present when both dimensions were cut as twenty foot lumber (longest possible) was evenly distributed in all package arrival data. Total number of boards processed, unlike many of the other variables, was dependent on cutting bill structure. Therefore, comments pertaining to this measure of performance will only refer to average number of boards processed per algorithm.

2.5.2 Setup Of Analysis

2.5.2.1 2 Way Anova Description

Two way analysis of variance (ANOVA) was used with three replications for each combination of factors (cutting bills and algorithms). Table 17 shows an abbreviated version of a 3" width value/fbm matrix in which the cell containing "*" is the third replication of a simulation run using algorithm 2 and cutting bill 1. Two large matrices, one for each lumber dimension, were generated.

Table 17. Example Of 3” Width Value/Fbm Table
(each replication or observation is a mean or total value/total input fbm)

	algorithm 1	algorithm 2	algorithm 3	.....	algorithm 20
cutting bill 1	.67074	.67074	.62074	.....	.70174
	.65234	.68314	.63314	.....	.71966
	.68193	.68235 *	.64723		.74116
:	:	:	:	:	:
:	:	:	:	:	:
:	:	:	:	:	:
cutting bill 7	.87323	.88132	.81249	.....	.84664
	.84286	.86359	.82203	.....	.87981
	.86006	.85279	.82315		.88371

Two way ANOVA was chosen for its ability to objectively determine if significant differences existed between the effects of a cutting bill or algorithm on value/fbm. Interactions or differences between how cutting bill (or algorithm) effected value/fbm at a given cutting algorithm (or bill) could also be measured. Appendix V provides a detailed description of the formulas and procedures associated with two way ANOVA.

Bartlett's test (see Appendix VI for details), a technique based on a statistic whose sampling distribution is approximated very closely by the chi-square distribution when k random samples are drawn from independent normal populations, tested the hypothesis:

$$H_o: \sigma_1^2 = \sigma_2^2 = \dots = \sigma_k^2$$

against:

H_1 : the variances are not all equal

A three factor table in which cutoff percentage was added to cutting bill and algorithm would have enhanced data analysis. Under the ideal setup, significant differences, if present, between cutoff percentages could have been objectively determined. However, such a setup would have excluded algorithms 20 (no priority settings) and 19 (mill settings).

2.5.2.2 Student-Newman-Keuls Range Test

If cutting algorithm or interaction means were found to be statistically different, a range test was used to examine all possible pairs of means and ascertain which ones were significantly different from each other. Student-Newman-Keuls (SNK) test was chosen out of the several that were available for its ability to handle large numbers of means and compatibility with Excel macros. Comparisons were made only between the 20 cutting algorithm means. Appendix VII shows the procedures involved in an SNK test and an example of it, respectively.

2.5.3 ANOVA Assumptions

ANOVA cannot be considered valid until all of three of its assumptions, listed below, have been fully satisfied:

- The population distribution being sampled is normal.
- The process is in control, that is, it is repeatable
- The variance of errors within all k levels of the factor is homogeneous

2.5.3.1 Normal Data

Normality of project data was confirmed by the central limit theorem which, according to Mandel (1984) is defined as follows:

“Given a population of values with a finite (non-infinite) variance, if we take independent samples from this population, all of size N , then the population formed by the averages of these samples will tend to have a Gaussian (normal) distribution, regardless of what the distribution is of the original population; the larger N , the greater will be this tendency towards normality.”

According to Sternstein (1996) and Spiegel (1992), normality status could be granted to samples sizes larger than 30. A total of 420 observations were contained within the 3” width ANOVA table, making all data normal even though it was skewed. Sample size could have also been interpreted as the number of replications per algorithm/cutting bill combination. If such an approach had been taken, additional data would have had to have been collected.

2.5.3.2 Repeatable Process

All data generation could easily be repeated by either changing random seeds in the simulation software or gathering information from future mill runs. Both dimensions of lumber are cut at least once a month at the participating mill.

2.5.3.3 Homogeneous Variances

Using Bartlett’s test with an α of 5%, all variances from ANOVA work were found to be homogeneous.

2.5.4 Comparing Analysis Variables

Comparisons between analysis variables were limited to correlation coefficient (ρ) calculations and plotting rankings due to the different units of measurement. Correlation coefficients for each

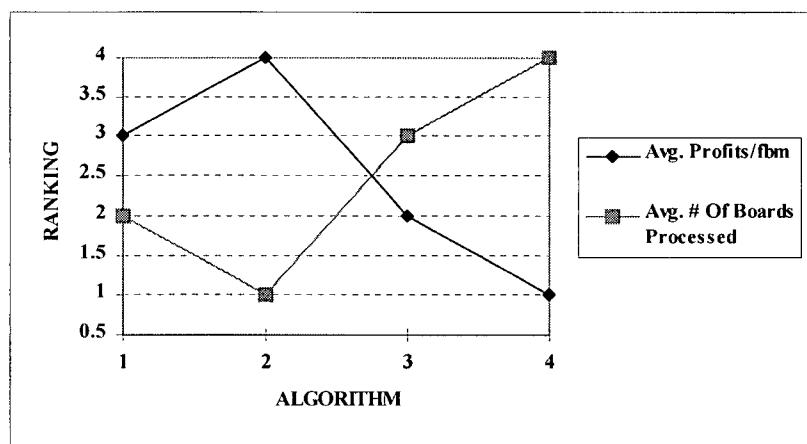
comparison between the main variable, value/fbm, and the other three variables were done using data from all algorithms.

Comparisons between analysis variables were done graphically by first ranking the data and then plotting the rankings on a bar graph. Rules for ranking data are discussed in subsequent sections of this thesis. As an example, Table 18 and Figure 14 show the ranked and plotted data of a four sample average value/fbm versus the average number of boards processed.

Table 18. Example Of Average Value/fbm versus Average Number Of Boards Processed Data

Algorithm	Average Value/fbm	Rank	Average Number Of Boards Processed	Rank
1	1.276	3	472	2
2	1.245	4	543	1
3	1.294	2	386	3
4	1.356	1	365	4

Figure 14. Rankings Graph Example - Value/fbm Versus Number Of Boards Processed



3.0 RESULTS AND DISCUSSION

3.1 3.75" Width Lumber

Appendix VIII and Table 19 show the 3.75" width value/fbm data matrix and F tests, respectively. 3.75" width value/fbm means were found to be homogeneous, therefore, Bartlett's test and other subsequent work was now considered irrelevant even though not much of a difference existed between the calculated and critical F values. Generating a second ANOVA table without cutting bills might have shown that 3.75" width value/fbm means were different; however, the statistical procedures had to be consistent for both lumber dimensions.

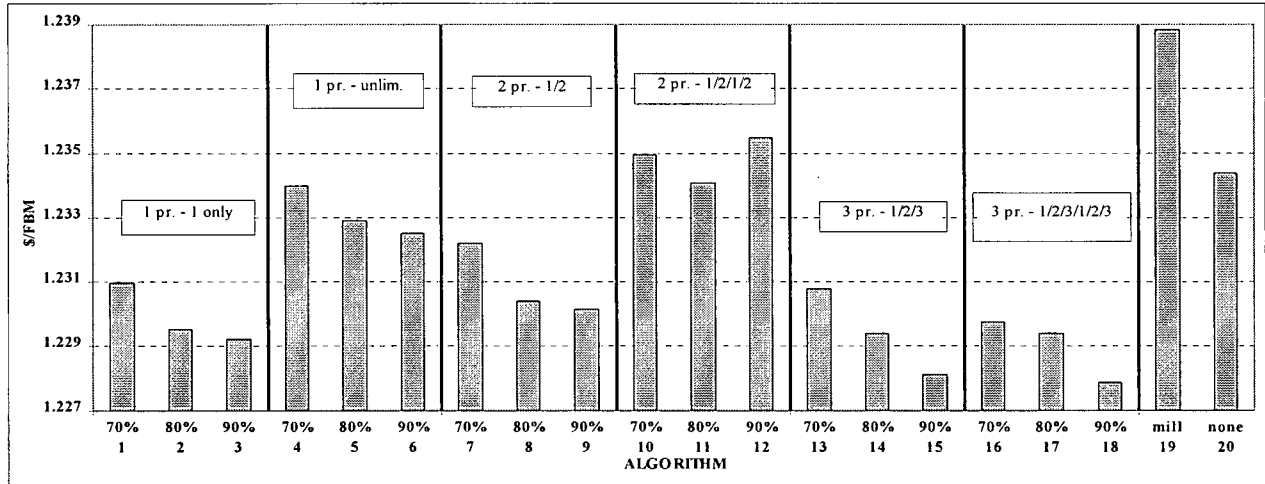
Table 19. ANOVA Table For 3.75" Width Lumber.

Source of Variation	SS	degrees of freedom	MS	F	P-value	F critical
Cutting Bills	0.13944	1	0.13944	3282.326	1.03E-66	3.960352
Algorithms	0.000924	19	4.86E-05	1.144302	0.32613	1.718025
Interaction	0.00024	19	1.27E-05	0.297811	0.997848	1.718025
Within	0.003399	80	4.25E-05			
Total	0.144002	119				

While one might say that using only two cutting bills for 3.75" width ANOVA analysis was a setup destined for statistical "failure" unless more data had been generated, all attempts had to be made to show that project findings were not only applicable to one dimension of lumber. Too many assumptions about the effects of grading rules and width would have been made if the project used one data matrix with nine cutting bills, 7 from 3" width and 2 from 3.75" width. Cutting bills from previous runs were readily available but information about when the priority settings were changed could not be found. Data from 3.75" width runs were presented for reference purposes only.

Figure 15 below shows 3.75" width value/fbm means. In algorithms which used priority settings, a 70% cutoff percentage produced the highest value/fbm results. The only exception to this trend was seen among algorithms 10, 11, and 12 which fared poorly in the 3" width analysis.

Figure 15. 3.75" Width Value/fbm



3.2 3" Width Lumber

3.2.1 Value/Fbm Means

Appendix IX and Table 20 show the 3" width data matrix and F test results, respectively. The F value of 20.90272 was decisively higher than the 5% critical value of 1.623819, therefore, algorithm means were significantly different.

Table 20. ANOVA Table For 3" Width Lumber.

Source of Variation	SS	degrees of freedom	MS	F	P-value	F critical
Cutting Bills	11.27962	6	1.879937	22774.36	0	2.131028
Algorithms	0.032783	19	0.001725	20.90272	4.4E-43	1.623819
Interaction	0.096539	114	0.000847	10.25892	3.79E-56	1.28545
Within	0.023113	280	8.25E-05			
Total	11.43206	419				

Table 21 shows that variances from the 3” width matrix produced a Bartlett’s test value (see Appendix X for complete data) of 1.404812 which was well below the 5% chi-square critical value of 30.143505.

Table 21. 3” Width Value/Fbm Bartlett’s Test Results

n	21	(# obs./cell)
N	420	(total # obs.)
k	20	(total # cells)
s ² p	0.028498	
q	0.620775	
h	1.017500	
S (1/(n-1))	1	
1/(N-k)	0.0025	
b	1.404812	
5% α	30.143505	

3.2.1.1 Differences

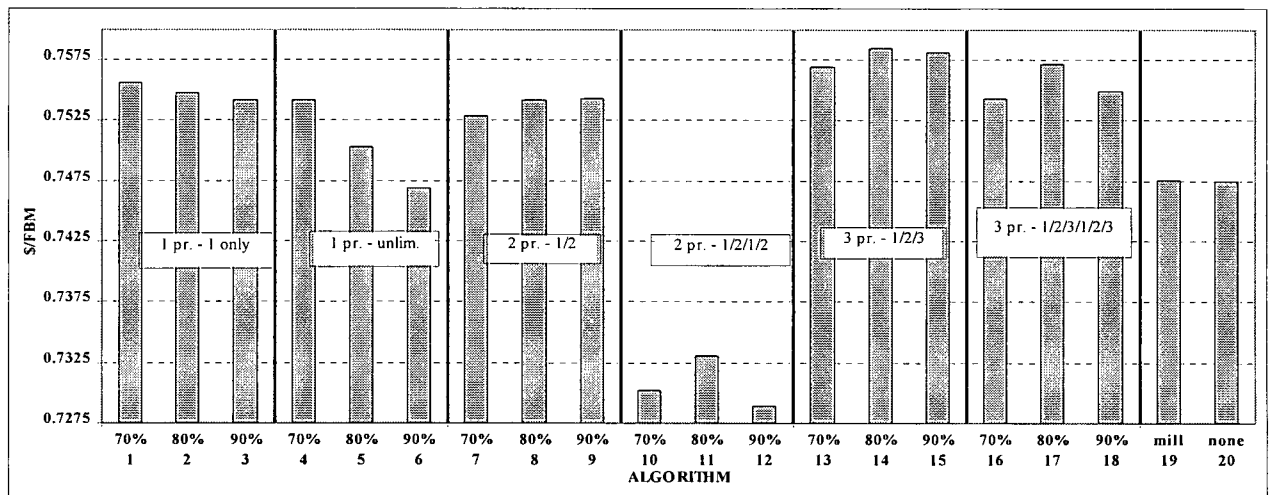
Expectations of finding algorithms which were decisively good disappeared quickly once it was found that a mere .0295/fbm difference existed between the highest and lowest ranked means. The SNK range test identified exactly which means were statistically similar or different from each other. Figure 16 below shows, graphically, all possible combinations of means. To make comparisons easier, mean values, not algorithm names, increase along the X or horizontal axis of the table from left to right while Y or vertical axis values decrease from the top to bottom row. If two means are similar, a “-----” appears in the matrix cell or intersection of the algorithms. Cells containing blanks and gray shading symbolize statistical differences and irrelevant comparisons, respectively.

Figure 16. Student-Newman-Keuls Comparison Of Means Table
(labels on X and Y coordinates = algorithm)

12	10	11	6	20	19	5	7	4	8	3	16	9	2	18	1	13	17	15	14	
						----	----	----	----	----	----	----	----	----	----	----	----	----	----	14
						----	----	----	----	----	----	----	----	----	----	----	----	----	----	15
						----	----	----	----	----	----	----	----	----	----	----	----	----	----	17
						----	----	----	----	----	----	----	----	----	----	----	----	----	----	13
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	1
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	18
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	2
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	9
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	16
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	3
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	8
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	4
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	7
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	5
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	19
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	20
			----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	6
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	11
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	10
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	12

Before any conclusions can be made about value/fbm means, it must be noted that significant interactions occurred in algorithms 10 to 12 as Figure 19 shows. When all algorithms were considered, significant differences existed primarily between two groups; algorithms 10, 11, 12, 6, 19, 20 and all the others. If algorithms 13, 14, 15, and 17 were excluded from comparisons, only algorithms 10 through 12 were different from the rest. Figure 17 below shows, in graph format, how all value/fbm means compare to each other.

Figure 17. 3" Width Value/FBM Means

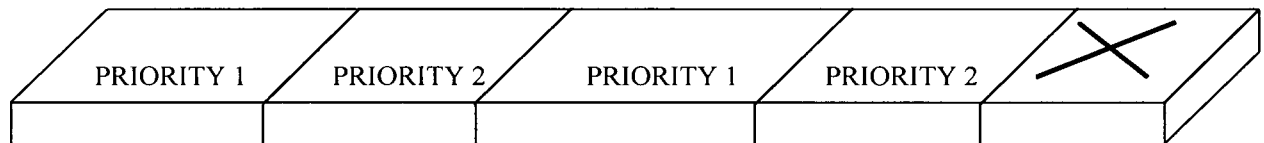


3.2.1.2 Number Of Parts Prioritized

Statistically, there was no single algorithm that could have been called the best. However, three of the top four “better” algorithms prioritized three different parts and forced one of each, if possible, into a section of lumber. Algorithm 14 which used an 80% cutoff point had the best value/fbm result at .7585/fbm while algorithms 15 (90% cutoff) and 13 (70% cutoff) ranked second and fourth, respectively.

Poor value/fbm results were always yielded when two items were prioritized and forced into a lumber section according to the diagram in Figure 18.

Figure 18. Cutting Prioritized Parts With Algorithms 10, 11, and 12
(alg. 10 cutoff = 70%, alg. 11 cutoff = 80%, alg. 12 cutoff = 90%)



Values from algorithms 10, 11, and 12 were so bad that the best performer of the three, algorithm 11, was 1.5 cents/fbm lower than the fourth worst performing algorithm. Large discrepancies between the 1/2/1/2 priority setup and 1 part algorithms were caused by the formers inability to quickly complete a part the way the latter did. Three part algorithms outperformed the 1/2/1/2 setup as the latter probably forced in more prioritized parts, hence fewer opportunities for “natural” optimization were available. When three different parts were prioritized, there were probably many instances where the third and subsequent parts were too long to be included in the cutting solution.

3.2.1.3 Cutoff Percentages

Figure 17 also shows that when one part was prioritized, maximum value/fbm values were achieved with a 70% cutoff percentage. Maximum two part prioritization values came from a 90% cutoff mark for algorithm 9 (1/2) while 80% was the optimal point for algorithm 11 (1/2/1/2). Three part prioritization was most compatible with an 80% cutoff percentage.

These results contradict the often mentioned “evils” of imposing restrictions on natural or optimal cutting patterns. Before any simulation data was generated, it was expected that algorithms with a 70% cutoff point would have rated highly as less time was spent on cutting prioritized parts. While data from runs involving only one prioritized part, algorithms 1 through 6, confirmed the benefits of a lower cutoff percentage, better value/fbm results were produced with an 80% or 90% mark when two or three parts were involved.

Ideally, a larger range of cutoff percentages would have been examined to possibly find a better algorithm. In most cases, peak values were found for each combination of parts and cutoff percentages. A notable exception occurred in algorithms 4 through 6 as a continuous decrease in value/fbm occurred as the cutoff mark increased. This pattern indicates that an algorithm based on unlimited cutting of one prioritized part and a cutoff percentage of 60% or 50% could have possibly outperformed algorithm 14.

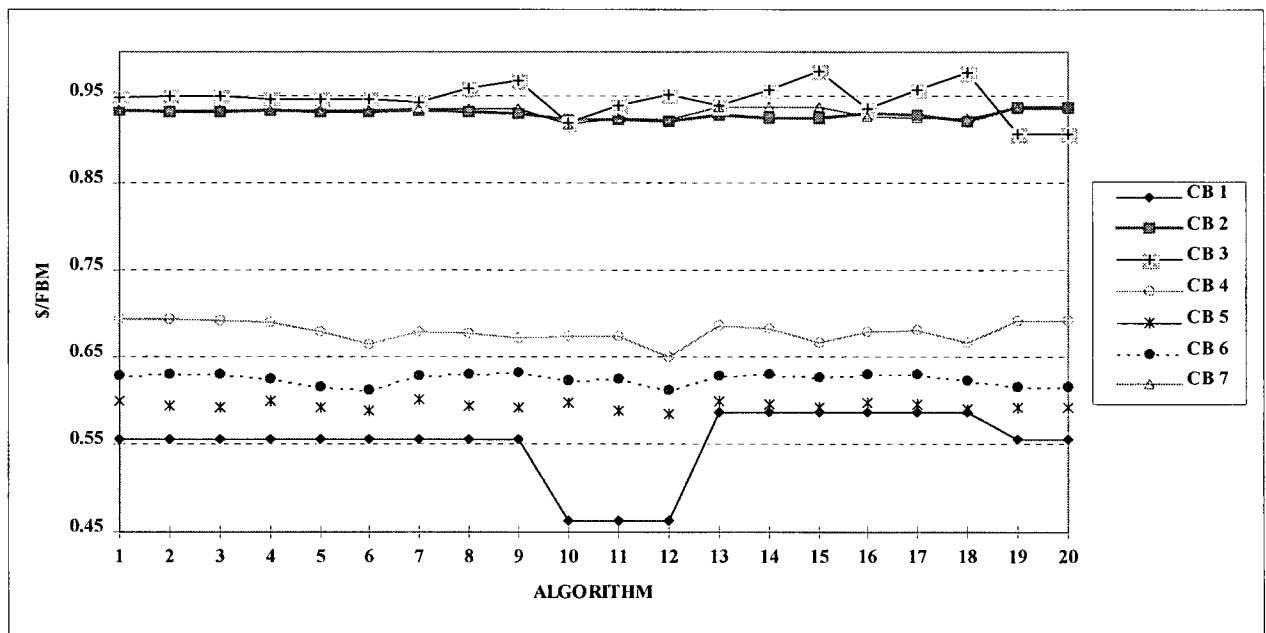
3.2.2 Interaction Results

Interaction or when a change in one factor produces a different change in the response variable at one level of another factor than at other levels of this factor was significant in the 3” width

ANOVA. As was shown in Table 20, 3" width interaction produced a calculated F value of 10.25892 while F critical was 1.28545.

Figure 19 below shows that the most obvious signs of interaction occurred when algorithms 10, 11, and 12 were applied to cutting bill 1, an order that had only nine parts while the other six bills had at least 15 items. Other noticeable deviations appear when cutting bill 3 and algorithms 8 through 20 are combined.

Figure 19. 3" Width Interaction Plot
(CB = cutting bill)



3.3 3" Width External Variables

Correlation coefficients were calculated and data ranking was done to determine if good value/fbm results were associated with poor performances of external variables. A complete data analysis was conducted to provide additional information for comparing cutting algorithms.

3.3.1 Number Of 20' Clears Added

Appendix XI shows 20' clears data from all 3" width simulation runs. Table 22 below shows that algorithm means were different while Bartlett's test, see Table 23 for results and Appendix XII for calculations, successfully validated variances.

Table 22. 3" Width Number Of 20' Clears Added ANOVA

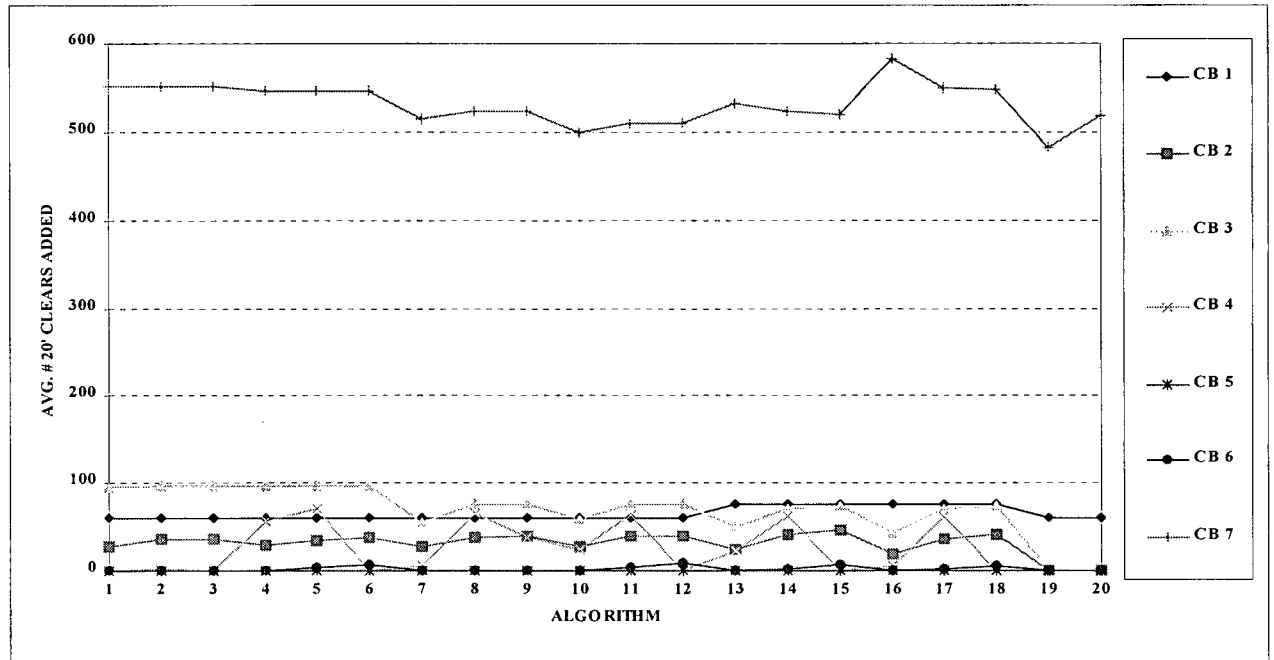
Source of Variation	SS	df	MS	F	P-value	F crit
Cutting Bills	13114279	6	2185713.1	4732.42	3.5E-278	2.131028
Algorithms	37110.152	19	1953.1659	4.228918	3.22E-08	1.623819
Interaction	99886.248	114	876.19515	1.897103	1.07E-05	1.28545
Within	129320.67	280	461.85952			
Total	13380596	419				

Table 23. 3" Width Number Of 20' Clears Added Bartlett's Test Results

n	21	(# obs./cell)
N	271	(total # obs.)
k	20	(total # cells)
s^2_p	42385.175	
q	1.157374	
h	1.027904	
$S(1/(n-1))$	1.59449	
$1/(N-k)$	0.00398	
b	2.59262	
5% α	30.14351	

Caution must be exerted before any official statements can be made about number of 20' clears added means as numerous sources of interaction appeared after a plot of means according to cutting bill (Figure 20) was done.

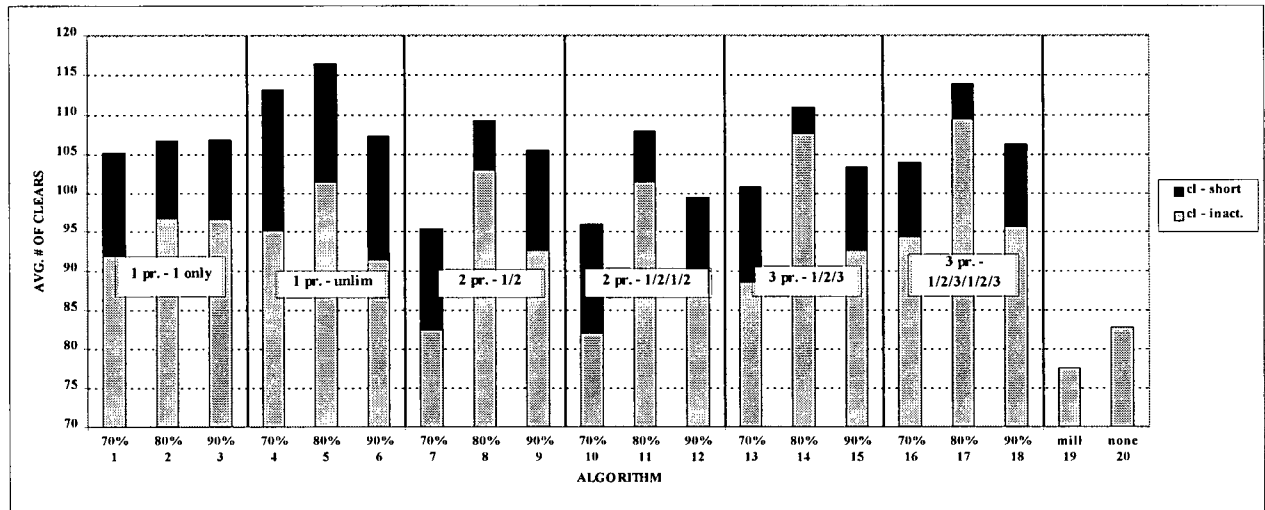
Figure 20. Interaction - Average Number Of 20' Clears Added



SNK tests on “number of 20’ clears added” means (data in Appendix XIII) proved that algorithms 19 and 20, mill settings and no priorities respectively, were significantly different from the rest. Figure 21 below shows a bar chart of average percentage of clears for each cutting algorithm.

Figure 21. Average Number Of Clears

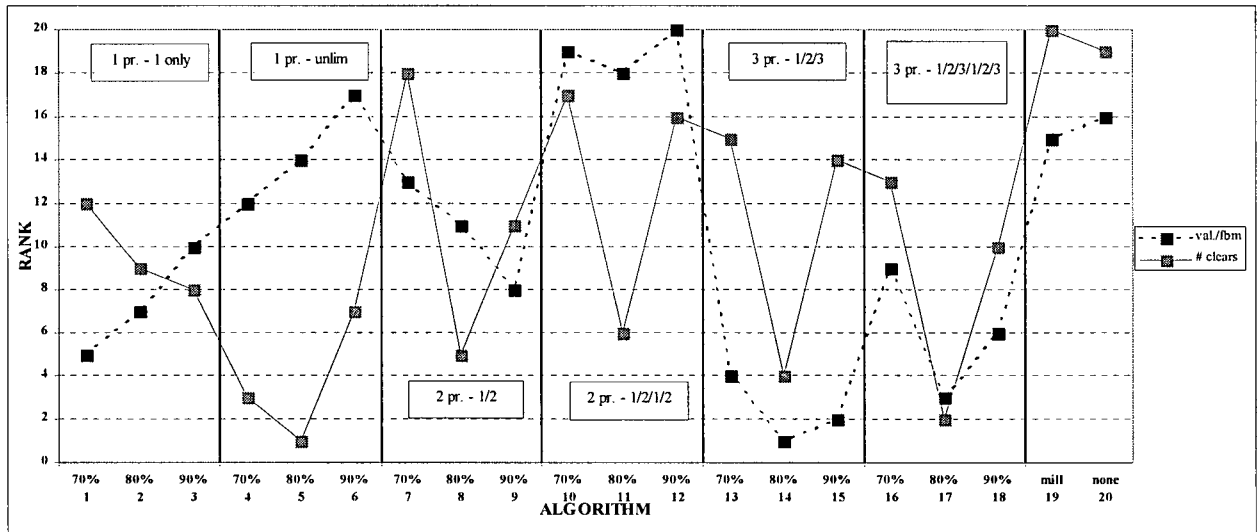
cl - short = clears added because the input lumber was shorter than the shortest part in the cutting bill.
 cl - inact. = clears added because no cutting bill parts had been cut in a five minute time period.



Twenty foot clears did not dominate the composition of completed boards in any of the 420 simulation runs as a maximum clears composition percentage of 13.77% was seen in six cutting bill 1 runs. In terms of maximum volume, 673 of the 8722 input boards for the cutting bill 7 run consisted of clears. An average of 103.39 clears or 2.41% were added to each run.

Algorithms with an 80% cutoff percentage tended to require more clears than others while minimal intervention was required for setups based on mill settings and no priorities. All algorithms had to “resort” to using clears and the range was a mere 39 boards. When average number of clears and value/fbm data was ranked in a way that gave higher ratings to larger values, Figure 22 below was derived.

Figure 22. Rank Comparisons - Number Of 20' Clears Added Vs. Value/fbm



When one part was prioritized, an inverse relationship existed between % clears and value/fbm. In all other algorithms, except 10 to 12, both variables of interest appeared to be correlated. A correlation coefficient of 0.29306 proved that no strong relationship existed between value/fbm and average number of clears when all algorithms were considered.

3.3.2 Number of Boards Processed

Appendix XIV shows the data matrix for this performance variable. Table 24 below shows that number of boards processed means were significantly different when ANOVA was applied to them while the Bartlett's test b value (0.134190 - see Appendix XV for data and Table 25 for results) was well under the 5% alpha chi-square limit.

Table 24. Number of Boards Processed ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Cutting Bills	3.35E+09	6	5.59E+08	99919.77	0	2.131028
Algorithms	371233.3	19	19538.59	3.493923	2.37E-06	1.623819
Interaction	2835193	114	24870.12	4.447315	2.01E-24	1.28545
Within	1565806	280	5592.164			
Total	3.36E+09	419				

Table 25. 3" Width Number of Boards Processed Bartlett's Test Results

n	21	(# obs./cell)
N	420	(total # obs.)
k	20	(total # cells)
s^2_p	8392518.910000	
q	0.059249	
h	1.016665	
$S(1/(n-1))$	0.952380952	
$1/(N-k)$	0.0025	
b	0.134190	
5% α	30.143505	

Statistically, number of boards processed interaction results were significant. However, a plot of the results in Figure 23 shows that the degree of severity was evenly spread out among the algorithms.

Figure 23. Interaction - Average Number Of Boards Processed

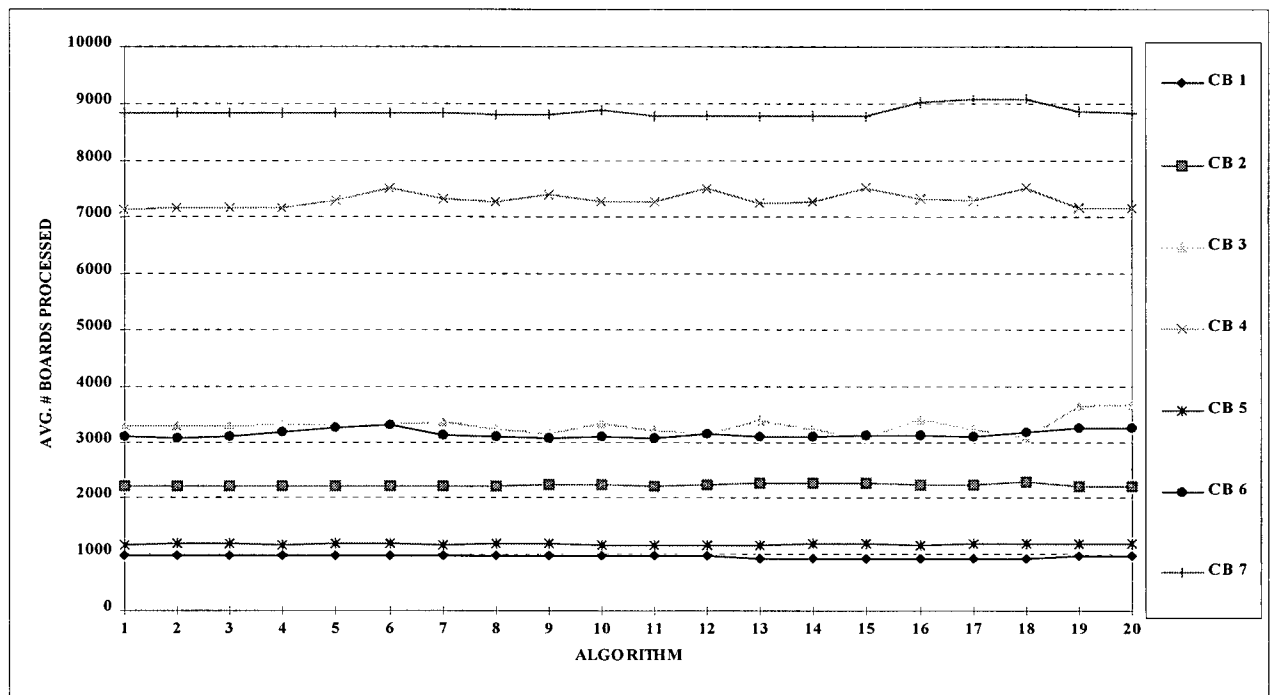
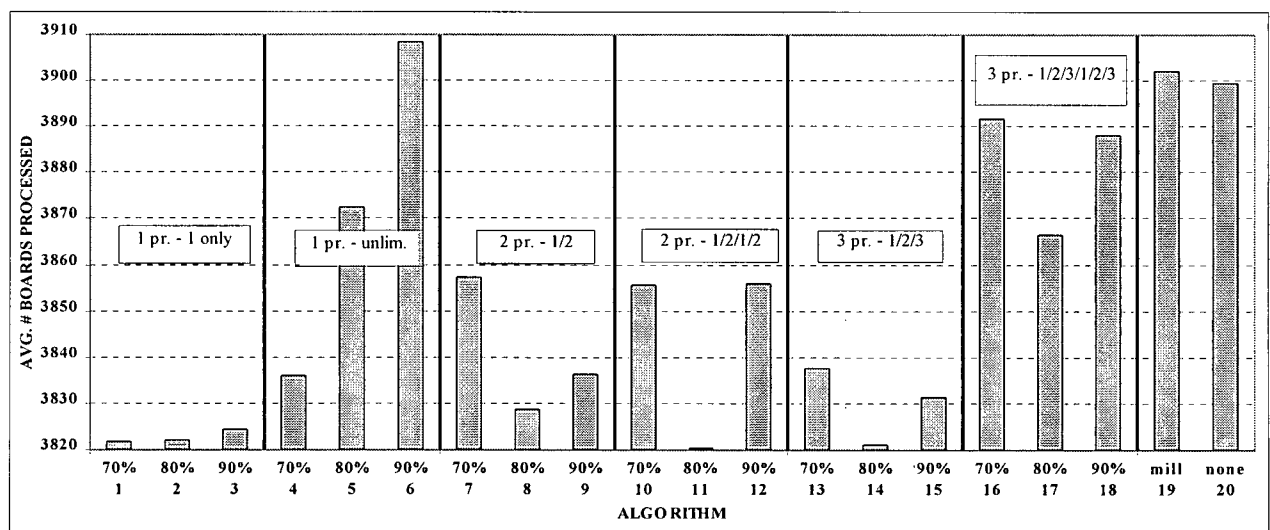


Figure 24 below shows a graph of the number of boards processed means. According to SNK results shown in Appendix XVI, algorithms 1, 2, 3, 8, 11, and 14 had lumber consumption means which were lower than the rest.

Figure 24. Average Number Of Boards Processed



As was shown earlier, algorithms 19 and 20 had the least amount of intervention and, as expected, ended up processing larger quantities of boards than most of the other setups. Algorithm 6, which allowed the least amount of optimization among one priority setups, required the most infeed boards. Although preliminary ANOVA proved that lumber consumption means were different, the range between the means was a respectable 88 boards or 37% of a package.

Figure 24 also shows that algorithms which rated highly in value/fbm analysis needed the fewest amount of full length lumber. A graphical comparison, Figure 25 below, was done by plotting the ratings or rankings of the two variables. A rating of 1 was given to the highest value of each variable although the lowest lumber consumption figure could have been interpreted as the best.

Figure 25. Rank Comparisons - Average Number Of Boards Processed Vs. \$/fbm

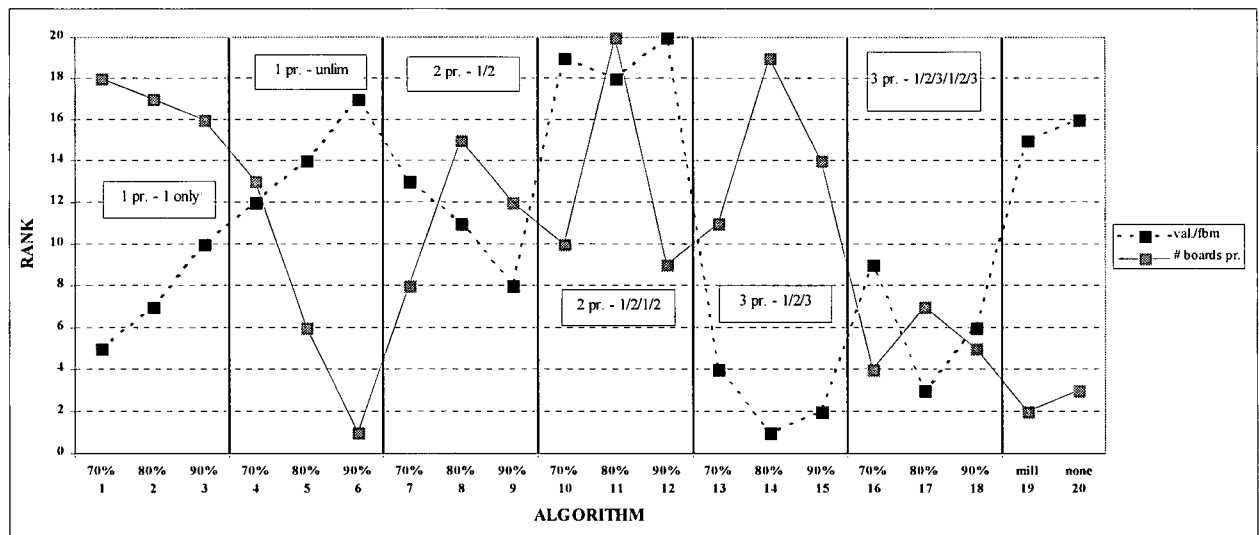


Figure 25 clearly shows that when 1 part is prioritized, value/fbm is inversely related to number of boards processed, a relationship which was also seen in algorithms 13 to 16 and the two setups

that did not use priority settings. Value/fbm and number of boards processed were almost completely independent as a -0.14559 correlation coefficient was derived from relevant data.

3.3.3 Percent Recovery Of Parts

Each cutting algorithm's level of efficiency was best measured by its ability to obtain a large yield of cutting bill parts relative to the amount of full length lumber that was fed into the chop saw. Appendix XVII shows the data matrix, ANOVA results appear in Table 26, Bartlett's results and data appear in Table 27 and Appendix XVIII, respectively.

Table 26. Percent Recovery Of Parts ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Cutting Bills	34284.027	6	5714.0045	2281.112	1.9E-234	2.131028
Algorithms	104.95303	19	5.5238436	2.205197	0.003071	1.623819
Interaction	881.07362	114	7.728716	3.085414	1.49E-14	1.28545
Within	701.3777	280	2.5049203			
Total	35971.431	419				

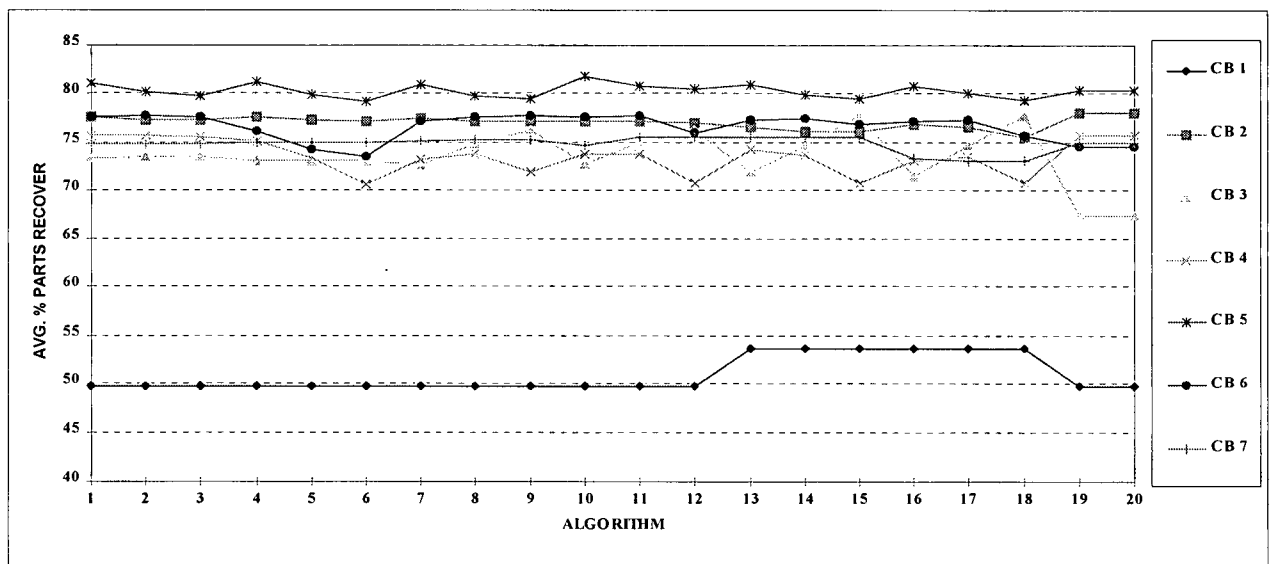
Table 27. 3" Width Percent Recovery Of Parts Bartlett's Test Results

n	21	(# obs./cell)
N	420	(total # obs.)
k	20	(total # cells)
s ² p	89.666196	
q	1.279695	
h	1.016665	
S (1/(n-1))	0.952381	
1/(N-k)	0.0025	
b	2.898325	
5% α	30.143505	

All ANOVA criteria was satisfied as means from all four 3" width analysis variables were found to be heterogeneous and relevant variances were homogeneous.

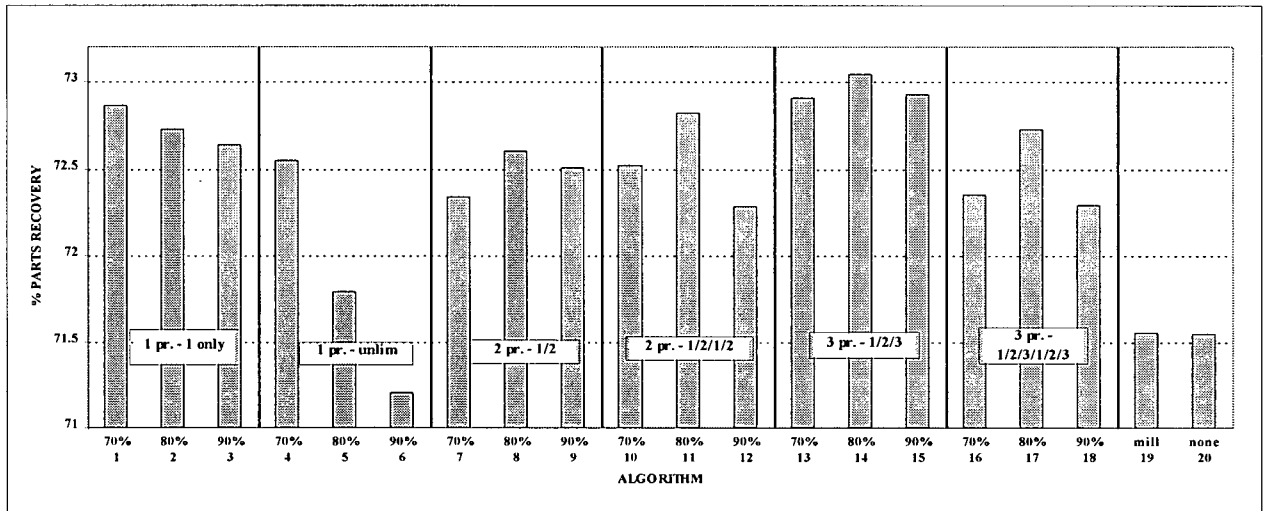
A plot of average percent recovery (Figure 26) showed that interactions were common, especially in algorithms 13 to 18.

Figure 26. Interaction - Average Percent Recovery Of Parts



Complete SNK data appears in Appendix XIX. Algorithm 6's parts recovery percentage of 71.196 was found to be significantly lower than those from other algorithms even though Figure 27 below shows that it was not much different from algorithms 19 and 20.

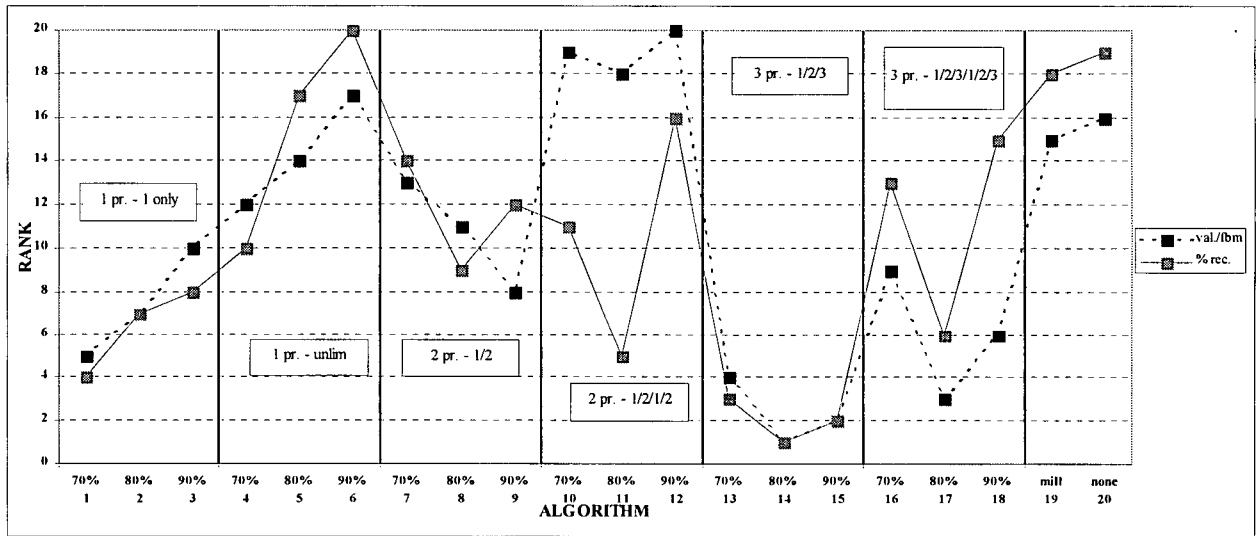
Figure 27. Percent Recovery Of Parts



Most of the algorithms which used priority settings posted parts recovery results that were about .5 to 1 percent better than mill settings and natural optimization. Algorithm 6, which yielded a disappointing 71.2%, was the only notable exception and reinforced the need for some optimization. Low recovery percentages for algorithms 19 and 20 can be explained by the lower amounts of 20' clears that they consumed.

After percent recovery of parts and value/fbm were ranked, the data were plotted to create Figure 28 below. Except for algorithms 10 to 12, a direct relationship appears to exist between the two variables, although the correlation coefficient was only 0.25489.

Figure 28. Rank Comparisons - Percent Recovery Of Parts Vs. \$/fbm



3.4 3" Width Financial Benefits Of The Ideal Algorithm

Total value lost in a year by using algorithm X instead of the highest rated algorithm (14) was calculated by the following formula:

$$(\text{Algorithm 14 Value/Fbm} - \text{Algorithm X Value/Fbm}) * (\text{Total Fbm Processed In One Year})$$

where:

Total Fbm Processed In One Year

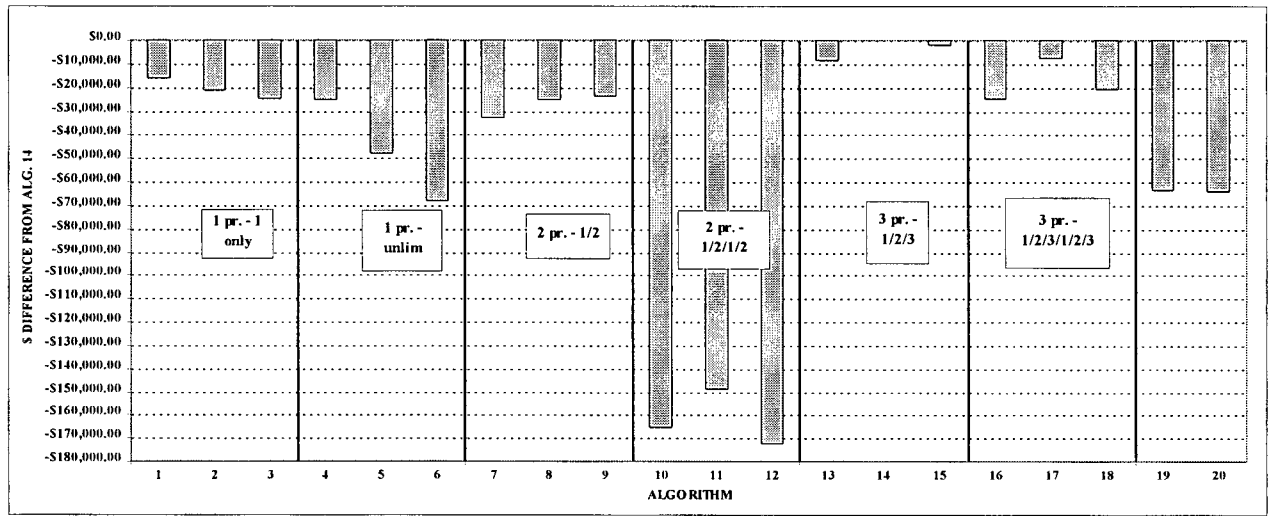
$$= (\text{Average fbm/hour from mill data}) * (\text{Total Number Of Operational Hours/Year})$$

$$= (1658.53 \text{ fbm/hour}) * (220 \text{ days/year}) * (16 \text{ hours/day})$$

$$= 5,838,041.53 \text{ fbm processed per year}$$

After a call was made to the mill to get operational parameters, it was found that a total of \$63,459.51 was gained by employing algorithm 14 instead of mill settings or algorithm 19. A table showing comparisons between algorithm 14 and all other setups appears in Appendix XX and Figure 29 below shows a bar chart of yearly value differences.

Figure 29. Yearly Value Differences From Algorithm 14.



4.0 SUMMARY AND RECOMMENDATIONS

4.1 Summary

A discrete simulation chop saw model capable of providing accurate estimates of mill production was successfully created. Time and production data from an existing chop saw mill were collected and used to create the model parameters. Extensive C programming was done to facilitate cutting decisions while lumber flow and tallying procedures were taken care of by the model's graphical network. Major limits to the model were the number of full length lumber sections that could be considered in a cutting decision and cutting accuracy. Modifications would have to be made to the current simulation model to make it compatible with other optimizing chop saws.

For 3" width lumber, data from simulation runs proved that algorithm 14 or the one that prioritized three different parts and forced one of each into a usable section of lumber with an 80% cutoff mark achieved the highest value/fbm figure. Statistically, this algorithm cannot be deemed the best as ANOVA analysis found two distinct groups of value/fbm means. No comparisons could be done among the algorithms with the 3.75" width data.

We can confidentially say that high value/fbm figures are obtained without sacrificing the performances of other important chop saw run variables. When three variables, number of 20' clears added, number of boards processed, and percent recovery of parts were compared to value/fbm, none of the correlation coefficients showed any relationships. Graphs of the ranked results showed that some trends did exist but only when one particular arrangement of priority settings was considered (example - 1 prioritized part, 1 forced in).

Financial gains were possible if new cutting algorithms were implemented. Yearly increases in value of \$63,459.51 and \$64,276.84 were obtainable over mill settings and no priority settings, respectively with algorithm 14 or the one with the highest value/fbm figure. If algorithm 12 or the worst performing one was used instead of mill settings, a financial loss of \$108,762.71 was incurred.

4.2 Recommendations

This project objectively proved that using priority settings in chop saw production is not as detrimental as was initially thought as setups based on mills settings and no prioritized parts were included with the lower ranked algorithms. Although project personnel were satisfied with the project results, there are definitely many opportunities for improvement over what was achieved. Below are some of the areas that can be expanded.

Data analysis for 3" width stock worked out well, however, most of its cutting bills consisted of 16 to 18 parts. A larger variety of bills would have been more desirable but none of the mill runs during the month of July included any large bills consisting of more than 20 parts. For 3.75" width lumber, only one cutting bill was worked on each time a mill visit was made.

In addition to providing more realistic data, adding more cutting bills to a project contributes to the statistical power of the tests. Future projects with more cutting bills can be conducted without excessive expenses by having mill staff monitor cutting bill data when a run is on and notifying the responsible individual when everything is completed.

There were no obvious signs during the project that a cutoff percentage between 70% and 90% was detrimental to value/fbm results. However, what if a 60% or 100% mark was present? It is not known if more clears will have to be added if a 100% point is used or what the possible added economic benefits from a 60% limit are. A project with more than the current three cutoff percentages would answer these questions.

Only one form of intervention, add 20' clears after 5 minutes of cutting bill inactivity, was present in the simulation model. By how much would costs go down if a 10, 15, or 20 minute inactivity level was used? Would costs increase significantly if a 2 or 3 minute intervention policy was followed? A very useful ANOVA analysis would be a three factor setup, see Appendix XXI, in which cutting algorithms are further categorized according to intervention time.

Algorithms which prioritized three different parts produced high value/fbm values if only one of each was forced into a lumber section. A project with algorithms including four or more different parts would determine if a "saturation point" or one where value decreases if too many parts are forced in exists.

5.0 LITERATURE CITED

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APPENDIX I.

DATA FROM BOTH GRADES OF LUMBER

(all prices in dollars/1000 board feet, ratio = std/#2 btr./ util/#3)

week	std/#2 btr.	util/#3	ratio	week	std/#2 btr.	util/#3	ratio
1/6/95	330	235	1.40	6/30/95	275	185	1.49
1/13/95	325	220	1.48	7/7/95	290	185	1.57
1/20/95	320	220	1.45	7/14/95	309	190	1.63
1/27/95	315	215	1.47	7/21/95	295	180	1.64
2/3/95	310	215	1.44	7/28/95	290	175	1.66
2/10/95	315	215	1.47	8/4/95	283	180	1.57
2/17/95	320	215	1.49	8/11/95	285	185	1.54
2/24/95	320	215	1.49	8/18/95	305	200	1.53
3/3/95	315	210	1.50	8/25/95	300	200	1.50
3/10/95	315	210	1.50	9/1/95	315	195	1.62
3/17/95	310	210	1.48	9/8/95	320	200	1.60
3/24/95	308	210	1.47	9/15/95	320	195	1.64
3/31/95	290	210	1.38	9/22/95	320	200	1.60
4/7/95	290	210	1.38	9/29/95	325	200	1.63
4/13/95	285	210	1.36	10/6/95	320	195	1.64
4/21/95	290	210	1.38	10/13/95	315	180	1.75
4/28/95	285	205	1.39	10/20/95	290	180	1.61
5/5/95	290	205	1.41	10/27/95	290	190	1.53
5/12/95	285	205	1.39	11/3/95	300	200	1.50
5/19/95	290	200	1.45	11/10/95	305	200	1.53
5/26/95	280	200	1.40	11/17/95	280	185	1.51
6/2/95	278	195	1.43	11/24/95	268	180	1.49
6/9/95	260	185	1.41	12/1/95	260	190	1.37
6/16/95	260	185	1.41	12/8/95	290	190	1.53
6/23/95	270	185	1.46	12/15/95	300	200	1.50

	Canadian \$	U.S. \$
average std/#2 btr. price (A)	298.12	417.37
average util/#3 price (B)	199.10	278.74
average ratio (A/B)	1.50	

APPENDIX II.

PROJECT CUTTING BILLS

3" Width Cutting Bill 1

Grade	Length	Kicker	Demand	Cut	Complete	Price
3	6.5	1	1100	0	0	0.14
4	35	7	50	0	0	0.015
1	36	3	430	0	0	1.81
3	36	5	320	0	0	0.85
1	72	7	270	0	0	3.34
4	84	7	10	0	0	0.07
1	144	0	50	0	0	12.49
1	168	0	60	0	0	15.57
1	192	0	60	0	0	19.24

3" Width Cutting Bill 2

Grade	Length	Kicker	Demand	Cut	Complete	Price
3	6.5	1	310	0	0	0.14
4	35	7	150	0	0	0.025
1	36	3	970	0	0	1.87
2	36	3	550	0	0	1.87
3	36	5	1800	0	0	1.48
1	48.425	6	220	0	0	3.06
1	60.236	7	220	0	0	3.8
1	72.047	7	590	0	0	4.55
4	84	7	10	0	0	0.07
1	96	0	510	0	0	6.5
2	96	0	60	0	0	5.2
2	120	0	200	0	0	12.41
1	144	0	120	0	0	14.91
2	144	0	120	0	0	14.89
1	168	0	40	0	0	17.39
1	192	0	40	0	0	19.88

3" Width Cutting Bill 3

Grade	Length	Kicker	Demand	Cut	Complete	Price
3	6.5	1	2300	0	0	0.14
1	24.803	6	1000	0	0	1.57
4	35	7	80	0	0	0.025
1	36	3	650	0	0	1.82
2	36	3	470	0	0	1.82
3	36	5	1800	0	0	1.5
1	48.425	6	490	0	0	3.07
1	60.236	7	390	0	0	3.82
1	72.047	7	980	0	0	4.56
4	84	7	20	0	0	0.07
1	96	0	700	0	0	7.4
2	96	0	200	0	0	7.4
1	144	0	210	0	0	12.75
2	144	0	180	0	0	12.75
1	168	0	10	0	0	15.47
1	192	0	10	0	0	19.27

3" Width Cutting Bill 4

Grade	Length	Kicker	Demand	Cut	Complete	Price
3	6.5	1	1200	0	0	0.14
1	36	5	4600	0	0	1.81
2	36	5	3500	0	0	1.81
3	36	3	5000	0	0	1.49
1	48.425	6	1500	0	0	3.01
1	60.236	6	1500	0	0	3.75
1	72.047	7	1300	0	0	4.48
4	84	7	60	0	0	0.07
1	96	0	120	0	0	6.46
2	96	0	430	0	0	4.96
1	144	0	120	0	0	12.49
2	144	0	170	0	0	12.49
1	168	0	40	0	0	15.52
2	168	0	30	0	0	15.52
1	192	0	30	0	0	19.24
2	192	0	10	0	0	19.24

3" Width Cutting Bill 5

Grade	Length	Kicker	Demand	Cut	Complete	Price
3	6.5	1	2200	0	0	0.14
1	36	5	1300	0	0	1.81
2	36	5	460	0	0	1.81
3	36	3	920	0	0	1.49
4	48	7	140	0	0	0.02
1	48.425	6	50	0	0	3.01
1	60.236	6	50	0	0	3.75
1	72.047	7	40	0	0	4.48
4	84	7	120	0	0	0.07
1	96	0	200	0	0	6.46
2	96	0	50	0	0	4.96
1	144	0	40	0	0	12.49
2	144	0	30	0	0	12.49
1	168	0	10	0	0	15.52
1	192	0	10	0	0	19.24

3" Width Cutting Bill 6

Grade	Length	Kicker	Demand	Cut	Complete	Price
3	6.5	1	1900	0	0	0.14
1	36	5	460	0	0	1.82
2	36	5	1300	0	0	1.6
3	36	3	5000	0	0	1.5
1	37.008	4	920	0	0	2.01
4	48	7	160	0	0	0.019
1	48.425	6	300	0	0	3.07
1	56.693	6	410	0	0	3.08
1	60.236	6	190	0	0	3.82
1	72.047	7	150	0	0	4.56
1	76.378	7	280	0	0	6.12
4	84	7	190	0	0	0.07
2	96	0	50	0	0	4.98
1	144	0	20	0	0	12.75
2	144	0	40	0	0	12.51

3" Width Cutting Bill 7

Grade	Length	Kicker	Demand	Cut	Complete	Price
3	6.5	1	4400	0	0	0.14
4	35	7	500	0	0	0.025
1	36	3	2900	0	0	1.81
2	36	3	2800	0	0	1.81
3	36	5	5200	0	0	1.49
3	40	5	750	0	0	1.655
1	48.425	6	1300	0	0	3.01
1	60.236	7	1400	0	0	3.75
1	72.047	7	1850	0	0	4.48
4	84	7	120	0	0	0.07
1	96	0	50	0	0	6.46
2	96	0	340	0	0	6.46
1	144	0	880	0	0	12.49
2	144	0	500	0	0	12.49
1	168	0	150	0	0	15.52
2	168	0	50	0	0	15.52
1	192	0	320	0	0	19.24
2	192	0	60	0	0	19.24

3.75" Width Cutting Bill 1

Grade	Length	Kicker	Demand	Cut	Complete	Price
3	6.5	1	10000	0	0	0.14
1	36	3	4000	0	0	2.59
2	36	3	1600	0	0	2.59
3	36	5	3900	0	0	1.4
4	48	7	110	0	0	0.04
1	49	3	1600	0	0	4.96
1	51	6	400	0	0	5.16
1	55	6	560	0	0	5.56
1	59	6	2700	0	0	5.97
1	72	7	243	0	0	8.5
1	76.378	7	670	0	0	9.58
1	78.74	0	2400	0	0	9.29
2	78.74	0	100	0	0	8.334
1	82.677	0	2100	0	0	9.76
4	84	7	60	0	0	0.08
2	96	0	300	0	0	10.17
1	120	0	600	0	0	13.41
1	144	0	180	0	0	15.25
2	144	0	450	0	0	15.25
1	157.48	0	20	0	0	17.88
1	168	0	110	0	0	15.45
2	168	0	10	0	0	17.79
1	192	0	70	0	0	19.15

3.75" Width Cutting Bill 2

Grade	Length	Kicker	Demand	Cut	Complete	Price
3	6.5	1	8800	0	0	0.14
1	36	3	2200	0	0	2.46
2	36	3	2500	0	0	2.59
3	36	5	3700	0	0	1.4
1	37.008	6	1200	0	0	3.17
4	48	7	80	0	0	0.04
1	49	3	2100	0	0	4.96
1	56.693	7	210	0	0	5.83
1	59	6	500	0	0	5.97
1	61	6	890	0	0	6.18
1	63	7	700	0	0	6.38
1	72	7	500	0	0	8.5
1	76.74	7	1250	0	0	11.34
1	78.74	0	1800	0	0	9.25
4	84	7	40	0	0	0.08
2	96	0	240	0	0	7.3
1	120	0	90	0	0	13.59
2	144	0	350	0	0	12.75
1	157.48	0	220	0	0	18.12

APPENDIX III.

DOWNTIME DATA

(** - Regular breaks were subtracted from downtime)

Item	Date	Shift (d/n)	Runtime	Adjusted Runtime	Worktime	Waiting Downtime	Random Downtime	**Adjusted Random Downtime
3" Width	6/3/97	d	14:38:31	3:29:05	2:19:00	25.00	1:10:05	0:25:05
3" Width	6/3/97	n	17:47:35	3:09:04	2:27:43	25.00	0:41:21	0:26:21
3" Width	6/4/97	d	11:58:47	8:00:00	3:01:18	66.67	4:58:42	0:28:42
3" Width	6/5/97	d	8:01:23	8:01:23	5:45:12	66.67	2:16:11	1:16:11
3" Width	6/6/97	d	8:38:26	8:00:00	4:51:17	66.67	3:08:43	2:08:43
3" Width	6/6/97	n	2:17:58	2:17:58	1:04:01	16.67	1:13:57	0:28:57
3" Width	6/6/97	n	2:37:00	2:37:00	0:57:35	16.67	1:39:25	0:24:25
3.75" Width	6/11/97	d	8:39:24	8:00:00	5:18:09	66.67	2:41:51	1:41:51
3.75" Width	6/13/97	d	8:32:52	8:00:00	5:23:19	66.67	2:36:41	1:36:41
3.75" Width	6/13/97	n	0:47:09	0:47:09	0:24:36	0.00	0:22:33	0:07:33
3" Width	6/20/97	d	8:29:46	8:00:00	4:30:48	66.67	3:29:12	2:29:12
3" Width	6/23/97	d	8:24:35	8:00:00	6:20:16	66.67	1:39:44	0:39:44
3" Width	6/23/97	n	10:17:05	9:47:05	7:45:54	75.00	2:01:11	1:01:11
3" Width	6/23/97	n	4:51:48	4:51:48	3:12:28	33.33	1:39:20	0:54:20
3" Width	6/24/97	d	8:35:01	8:00:00	5:22:04	66.67	2:37:56	1:37:56
3" Width	6/24/97	n	5:12:05	5:12:05	3:07:29	41.67	2:04:36	1:19:36
3" Width	6/24/97	n	2:06:22	2:06:22	1:30:55	16.67	0:35:27	0:20:27
3.75" Width	7/3/97	d	8:39:36	8:00:00	5:12:02	66.67	2:47:58	1:47:58
3.75" Width	7/4/97	d	15:34:53	8:00:00	5:33:22	66.67	2:26:38	1:26:38
3.75" Width	7/4/97	n	6:55:10	6:55:10	4:12:13	50.00	2:42:57	1:27:57

APPENDIX IV.

FINGERJOINTING RULES

Dimension	Cutting Bill	Grade	Minimum Length	Price/Inch	Kicker
3" Width	1	1	8	0.04	2
		2	8	0.02	4
3" Width	2	1	8	0.05	2
		2	8	0.03	2
		3	8	0.015	4
3" Width	3	1	8	0.05	2
		2	8	0.02	2
		3	8	0.01	4
3" Width	4	1	8	0.04	2
		2	8	0.021	2
		3	8	0.012	4
3" Width	5	1	8	0.04	2
		2	8	0.01	2
3" Width	6	1	8	0.04	2
		2	8	0.02	2
		3	10	0.015	4
3" Width	7	1	8	0.05	2
		2	8	0.02	2
		3	8	0.01	4
3.75" Width	1	1	8	0.06	2
		2	8	0.02	2
		3	8	0.01	4
3.75" Width	2	1	8	0.06	2
		2	8	0.02	2
		3	8	0.01	4

APPENDIX V.

TWO WAY ANOVA PROCEDURES

Spreadsheet (Excel) macros were used to open text files containing results from simulation runs and copy relevant information to the ANOVA matrix. Formulas programmed into spreadsheet cells calculated statistics which helped identify components of the ANOVA model, shown below:

$$Y_{ijk} = \mu + \tau_{ij} + \varepsilon_{k(ij)}$$

$$\tau_{ij} = A_i + B_j + AB_{ij}$$

where:

- $i = 1, \dots, 20$ for the 20 cutting algorithms
 $j = 1, \dots, 6$ for the 6 cutting bills
 $k = 1, 2, 3$ for the three observations in each i, j treatment combination
 Y_{ijk} = cell value or observation
 μ = population mean
 τ_{ij} = treatment effects:
 A_i = cutting algorithm effect
 B_j = cutting bill effect
 AB_{ij} = interaction
 $\varepsilon_{k(ij)}$ = error within each of the 120 treatments

All coordinates of an ANOVA table were covered by the spreadsheet data analysis program.

Locations of totals from columns ($T_{i..}$), rows ($T_{.j}$), and the entire table ($T_{...}$) are shown below.

Locations Of Two Way ANOVA Data

Y_{ijk} = one replication/observation

		CUTTING ALGORITHM						
		1	2	3	4	.....	20	
CUTTING BILL	1	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	.....	$(Y_{ijk})^*3$	$T_{1.}$
	2	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	.....	$(Y_{ijk})^*3$	$T_{2.}$
	3	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	.....	$(Y_{ijk})^*3$	$T_{3.}$
	4	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	.....	$(Y_{ijk})^*3$	$T_{4.}$
	5	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	.....	$(Y_{ijk})^*3$	$T_{5.}$
	6	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	$(Y_{ijk})^*3$	.....	$(Y_{ijk})^*3$	$T_{6.}$
		$T_{1..}$	$T_{2..}$	$T_{3..}$	$T_{4..}$	.....	$T_{20.}$	$T_{...}$

Sums of squares (SS) and mean squares (MS) data were then generated from the statistics by formulas in the table below:

Sums Of Squares and Mean Squares Formulas

Source	degrees of freedom	Sums Of Squares (SS)	Mean Squares (MS)
Cutting Algorithms A_i	$a - 1$	$\sum_i \frac{T_{i..}^2}{nb} - \frac{T^2}{nab}$	$\frac{SS_{A_i}}{a - 1}$
Cutting Bills B_j	$b - 1$	$\sum_j \frac{T_{.j.}^2}{na} - \frac{T^2}{nab}$	$\frac{SS_{B_j}}{b - 1}$
A X B Interaction	$(a - 1)(b - 1)$	$\sum_i \sum_j \frac{T_{ij.}^2}{n} - \sum_i \frac{T_{i..}^2}{nb} - \sum_j \frac{T_{.j.}^2}{na} + \frac{T^2}{nab}$	$\frac{SS_{A_i B_j}}{(a - 1)(b - 1)}$
Error $\epsilon_{k(ij)}$	$ab(n - 1)$	$\sum_i \sum_j \sum_k Y_{ijk}^2 - \sum_i \sum_j \frac{T_{ij.}^2}{n}$	$\frac{SS_{\epsilon_{k(ij)}}}{ab(n - 1)}$
Total	$abn - 1$	$\sum_i \sum_j \sum_k Y_{ijk}^2 - \frac{T^2}{nab}$	

F values for all sources (cutting bills, cutting algorithms, and interaction) were derived by dividing mean square error ($MS_{\epsilon_{k(ij)}}$) into the MS values. For each source, critical F values at $\alpha = 5\%$ (significance level) were extracted from an F table by using degrees of freedom from error and source. Differences within an ANOVA source (interaction, factors) were considered to be statistically significant if calculated F values exceeded critical values.

APPENDIX VI.

BARTLETT'S TEST PROCEDURES/EXAMPLE

Excel spreadsheets, using the steps below, facilitated Bartlett's calculations (courtesy of Walpole (1974)):

- compute k sample variances $s^2_1, s^2_2, \dots, s^2_k$ from samples of size n_1, n_2, \dots, n_k with $\sum_{i=1}^k n_i = N$

- combine the sample variances to give the pooled estimate

$$s_p^2 = \frac{\sum_{i=1}^k (n_i - 1) s_i^2}{N - k}$$

- calculate the b statistic

$$b = 2.3026 \frac{q}{h}$$

where:

$$q = (N - k) \log s_p^2 - \sum_{i=1}^k (n_i - 1) \log s_i^2 \quad \text{and} \quad h = 1 + \frac{1}{3(k-1)} \left[\sum_{i=1}^k \frac{1}{n_i - 1} - \frac{1}{N - k} \right]$$

- choose an α (eg. 5%) level of significance and a critical chi-square value (B)
- if $b > B$ reject hypothesis; otherwise fail to reject

Example:

Take four value/fbm variances from an ANOVA table as shown in the table below.

ANOVA Table For Bartlett's Example
- each σ^2 based on 21 (3 per cell * 7 cutting bills) algorithm observations

		ALGORITHM			
		1	2	3	4
CUTTING BILL	1	3 obs	3 obs	3 obs	3 obs
	2	3 obs	3 obs	3 obs	3 obs
	3	3 obs	3 obs	3 obs	3 obs
	:	3 obs	3 obs	3 obs	3 obs
	:	3 obs	3 obs	3 obs	3 obs
	:	3 obs	3 obs	3 obs	3 obs
	7	3 obs	3 obs	3 obs	3 obs
		σ^2_1	σ^2_2	σ^2_3	σ^2_4

hypothesis: $H_0: \sigma_1^2 = \sigma_2^2 = \sigma_3^2 = \sigma_4^2$
 H_1 : The variances are not all equal

$$n_1 = n_2 = n_3 = n_4 = 21, N = 84, k = 4$$

$$\alpha = 0.05, \text{ therefore } B = 7.81$$

$$\sigma_1^2 = 8.469E-05, \sigma_2^2 = 1.344E-05, \sigma_3^2 = 1.236E-05, \sigma_4^2 = 3.999E-05$$

$$s_p^2 = \frac{(21)(8.469E-05) + (21)(1.344E-05) + (21)(1.236E-05) + (21)(3.999E-05)}{80}$$

$$= 0.000038$$

$$q = (80)\log(0.000038) - [(21)\log(8.469E-05) + (21)\log(1.344E-05) + (21)\log(1.236E-05) + (21)\log(3.999E-05)]$$

$$= 11.029478$$

$$h = 1 + \frac{1}{9} \left(\frac{1}{20} + \frac{1}{20} + \frac{1}{20} + \frac{1}{20} + \frac{1}{20} - \frac{1}{80} \right)$$

$$= 1.020833$$

$$b = \frac{(2.3026)(11.029478)}{1.020833}$$

$$= 24.878180$$

$b > B$ or $24.878180 > 7.81$ therefore, reject H_0 , variances are not equal

APPENDIX VII.

SNK PROCEDURES/EXAMPLE

Below are the steps that were taken each time a SNK test was done (courtesy of Hicks (1993)):

- Arrange the 20 means in order from lowest to highest.
- Calculate standard error of the mean ($S_{\bar{Y}_j}$) for each treatment:

$$S_{\bar{Y}_j} = \sqrt{\frac{\text{error mean square}}{\text{number of observations in } \bar{Y}_j}}$$

- Using ANOVA table parameters, get significant ranges from a Studentized range table. Below is a table showing the 19 (number of means minus one) ranges that were chosen by using an α of 5% and 240 degrees of freedom from error mean square.

Studentized Range Table

# Of Means Compared	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Range @ 5% α	2.77	3.32	3.63	3.86	4.03	4.17	4.29	4.39	4.47	4.55	4.62	4.68	4.74	4.8	4.84	4.89	4.93	4.97	5.01

- Create a group of least significant ranges by multiplying by $S_{\bar{Y}_j}$ each range from step 3.
- Test all 190 possible ranges or combinations of means. Two given means are significantly different if their difference is greater than the least significant range value for the interval under consideration.
- Draw up a diagram or table showing all the means in order and their relationships (significant/not significant) to each other.

Example Of SNK Test:

Value/fbm means in order: #1 = 0.7585 #2 = 0.7581 #3 = 0.7302

Standard error of the mean from ANOVA table: 0.00198

Significant ranges based on $\alpha = 5\%$ and 30 degrees of freedom: 2 = 2.89 3 = 3.48

Least significant ranges (LSR):

$$2 = (0.00198)(2.89) = 0.00573 \qquad 3 = (0.00198)(3.48) = 0.00690$$

Test all ranges:	#1 & #2	difference = 0.0004	< LSR (.00573)	not different
	#1 & #3	difference = 0.0283	> LSR (.00690)	different
	#2 & #3	difference = 0.0279	> LSR (.00573)	different

APPENDIX VIII

3.75" WIDTH DATA MATRIX

		ALGORITHM																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
CUTTING BILL	1	1.2705	1.2710	1.2709	1.2684	1.2699	1.2702	1.2660	1.2669	1.2678	1.2714	1.2726	1.2736	1.2632	1.2616	1.2609	1.2632	1.2637	1.2642	1.2747	1.2712
		1.2575	1.2551	1.2551	1.2626	1.2602	1.2618	1.2605	1.2595	1.2582	1.2672	1.2638	1.2609	1.2610	1.2599	1.2542	1.2599	1.2599	1.2518	1.2704	1.2615
		1.2716	1.2679	1.2671	1.2734	1.2739	1.2736	1.2690	1.2665	1.2659	1.2707	1.2724	1.2753	1.2697	1.2672	1.2653	1.2690	1.2686	1.2671	1.2739	1.2590
2		1.2040	1.2036	1.2036	1.2032	1.2034	1.2029	1.2054	1.2023	1.2025	1.2075	1.2046	1.2062	1.1990	1.1976	1.1978	1.1977	1.1976	1.1979	1.2085	1.2087
		1.1811	1.1815	1.1825	1.1950	1.1904	1.1905	1.1939	1.1887	1.1880	1.1896	1.1880	1.1936	1.1930	1.1908	1.1915	1.1902	1.1888	1.1893	1.2005	1.2006
		1.2012	1.1982	1.1961	1.2012	1.1995	1.1959	1.1983	1.1984	1.1985	1.2033	1.2031	1.2033	1.1990	1.1993	1.1991	1.1985	1.1977	1.1970	1.2052	1.2052

MEAN	1.23098	1.22955	1.22922	1.23397	1.23288	1.23248	1.23218	1.23038	1.23015	1.23495	1.23408	1.23548	1.23082	1.23082	1.22940	1.22813	1.22975	1.22938	1.22788	1.23884	1.23437
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APPENDIX IX

3" WIDTH VALUE/FBM MEANS DATA MATRIX

ALGORITHM

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0.5644	0.5644	0.5644	0.5644	0.5644	0.5644	0.5648	0.5648	0.5648	0.4763	0.4763	0.4763	0.5757	0.5757	0.5757	0.5757	0.5757	0.5757	0.5644	0.5644
	0.5556	0.5556	0.5556	0.5556	0.5556	0.5556	0.5556	0.5556	0.5556	0.4550	0.4550	0.4550	0.5661	0.5661	0.5661	0.5661	0.5661	0.5661	0.5556	0.5556
	0.5460	0.5460	0.5460	0.5460	0.5460	0.5460	0.5460	0.5460	0.5460	0.4553	0.4553	0.4553	0.6148	0.6148	0.6148	0.6148	0.6148	0.6148	0.5460	0.5460
2	0.9314	0.9301	0.9301	0.9310	0.9283	0.9283	0.9298	0.9266	0.9264	0.9208	0.9166	0.9160	0.9322	0.9209	0.9196	0.9314	0.9224	0.9135	0.9364	0.9362
	0.9386	0.9355	0.9347	0.9379	0.9367	0.9344	0.9386	0.9355	0.9346	0.9296	0.9271	0.9265	0.9370	0.9327	0.9297	0.9355	0.9355	0.9227	0.9407	0.9404
	0.9303	0.9289	0.9286	0.9313	0.9294	0.9288	0.9289	0.9291	0.9290	0.9158	0.9224	0.9206	0.9115	0.9183	0.9228	0.9202	0.9245	0.9242	0.9350	0.9347
3	0.9468	0.9462	0.9462	0.9464	0.9461	0.9461	0.9289	0.9503	0.9594	0.8992	0.9290	0.9405	0.9296	0.9492	0.9752	0.9196	0.9482	0.9745	0.9103	0.9079
	0.9516	0.9544	0.9544	0.9497	0.9496	0.9496	0.9526	0.9664	0.9797	0.9307	0.9469	0.9652	0.9504	0.9625	0.9816	0.9495	0.9623	0.9815	0.9073	0.9061
	0.9444	0.9446	0.9446	0.9391	0.9391	0.9391	0.9448	0.9575	0.9634	0.9228	0.9415	0.9464	0.9324	0.9588	0.9759	0.9370	0.9594	0.9759	0.9009	0.9027
4	0.6907	0.6914	0.6905	0.6881	0.6825	0.6582	0.6709	0.6859	0.6830	0.6681	0.6798	0.6440	0.6879	0.6860	0.6616	0.6708	0.6837	0.6603	0.6911	0.6910
	0.6964	0.6938	0.6940	0.6942	0.6881	0.6677	0.6854	0.6759	0.6676	0.6852	0.6831	0.6543	0.6892	0.6904	0.6691	0.6855	0.6898	0.6699	0.6945	0.6944
	0.6923	0.6921	0.6923	0.6854	0.6662	0.6642	0.6787	0.6710	0.6652	0.6648	0.6568	0.6490	0.6783	0.6718	0.6659	0.6779	0.6708	0.6651	0.6908	0.6909
5	0.6036	0.5995	0.5980	0.6050	0.6048	0.5975	0.6034	0.6042	0.5991	0.6014	0.6018	0.6005	0.6042	0.6057	0.5998	0.6023	0.6026	0.5987	0.5961	0.5961
	0.5992	0.5917	0.5869	0.5981	0.5829	0.5828	0.6005	0.5874	0.5867	0.5972	0.5721	0.5701	0.5989	0.5899	0.5873	0.5954	0.5874	0.5846	0.5897	0.5897
	0.5944	0.5900	0.5878	0.5952	0.5895	0.5853	0.5959	0.5905	0.5863	0.5939	0.5883	0.5850	0.5952	0.5898	0.5873	0.5941	0.5960	0.5869	0.5880	0.5880
6	0.6278	0.6291	0.6276	0.6252	0.6155	0.6122	0.6273	0.6288	0.6301	0.6212	0.6220	0.6066	0.6278	0.6283	0.6247	0.6287	0.6292	0.6199	0.6153	0.6153
	0.6316	0.6323	0.6329	0.6322	0.6189	0.6155	0.6313	0.6322	0.6331	0.6261	0.6294	0.6206	0.6319	0.6325	0.6305	0.6320	0.6336	0.6255	0.6189	0.6189
	0.6264	0.6282	0.6267	0.6138	0.6132	0.6093	0.6249	0.6280	0.6298	0.6210	0.6206	0.6084	0.6257	0.6264	0.6246	0.6264	0.6271	0.6212	0.6123	0.6123
7	0.9290	0.9290	0.9290	0.9294	0.9294	0.9294	0.9315	0.9313	0.9313	0.9167	0.9164	0.9164	0.9307	0.9326	0.9326	0.9357	0.9290	0.9290	0.9359	0.9358
	0.9398	0.9398	0.9398	0.9402	0.9402	0.9402	0.9397	0.9415	0.9415	0.9272	0.9374	0.9359	0.9431	0.9416	0.9423	0.9312	0.9326	0.9331	0.9382	0.9385
	0.9287	0.9287	0.9287	0.9292	0.9292	0.9292	0.9304	0.9293	0.9293	0.9052	0.9157	0.9157	0.9336	0.9338	0.9338	0.9100	0.9103	0.9104	0.9322	0.9318
MEAN	0.75567	0.75482	0.75423	0.75416	0.75027	0.74685	0.75285	0.75418	0.75438	0.73017	0.73302	0.72897	0.75696	0.75847	0.75814	0.75428	0.75719	0.75493	0.74760	0.74746

APPENDIX X.

3" WIDTH VALUE/FBM - BARTLETT'S TEST

#	s^2	$s^2 * (\# \text{ obs} - 1)$	$(\log(s^2)) * (\# \text{ obs} - 1)$
1	0.027682967	0.55366	-31.15575
2	0.027845926	0.55692	-31.10477
3	0.027999301	0.55999	-31.05706
4	0.027814767	0.55630	-31.11449
5	0.028569014	0.57138	-30.88209
6	0.029185644	0.58371	-30.69661
7	0.027690377	0.55381	-31.15342
8	0.028756861	0.57514	-30.82517
9	0.029578732	0.59157	-30.58041
10	0.031701786	0.63404	-29.97833
11	0.033742136	0.67484	-29.43655
12	0.035403935	0.70808	-29.01897
13	0.025506045	0.51012	-31.86714
14	0.026696524	0.53393	-31.47091
15	0.028706661	0.57413	-30.84035
16	0.025219877	0.50440	-31.96514
17	0.026233894	0.52468	-31.62274
18	0.028136308	0.56273	-31.01466
19	0.026769945	0.53540	-31.44705
20	0.026723061	0.53446	-31.46228

APPENDIX XI.

20' CLEARS ADDED DATA MATRIX

	ALGORITHM																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67	63 54 67
2	28 23 33	33 32 42	33 35 43	28 22 36	35 27 42	35 27 43	32 20 33	40 31 42	40 35 42	32 19 32	42 34 41	43 35 42	25 16 32	44 33 49	49 42 51	22 10 27	39 24 45	39 38 46	0 0 0	0 0 0
3	89 92 103	92 96 103	92 96 103	90 95 103	92 97 103	92 97 103	40 57 71	73 73 82	73 73 82	50 55 71	72 73 85	75 73 82	48 51 49	69 66 79	73 69 79	28 49 54	69 66 79	73 69 79	0 0 0	0 0 0
4	0 0 0	0 3 0	0 2 0	81 62 30	112 100 0	0 0 0	7 10 0	106 89 0	114 0 0	29 44 0	104 89 0	0 0 0	40 30 0	102 87 0	0 0 0	0 16 0	100 87 0	0 0 0	0 0 0	0 0 0
5	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0
6	0 0 0	0 0 0	0 0 0	0 0 0	6 1 5	10 3 9	0 0 0	0 0 0	0 0 0	0 0 0	4 1 7	9 9 9	0 0 0	1 0 2	7 4 8	0 0 0	3 0 4	6 3 6	0 0 0	0 0 0
7	588 525 542	588 525 542	588 525 542	583 520 538	583 520 538	583 520 538	550 483 515	551 493 528	551 493 528	539 471 489	539 476 513	539 476 513	561 478 559	541 499 530	541 490 530	673 569 507	608 545 495	608 537 499	549 420 476	549 481 525
MEAN	105.095	106.667	106.810	113.048	116.429	107.238	95.333	109.143	105.476	95.952	107.810	99.476	100.762	110.905	103.333	103.905	113.857	106.190	77.571	82.810

APPENDIX XII.

3" WIDTH NUMBER OF 20' CLEARS ADDED (INTERVENTION) - BARTLETT'S TEST

#	n	1/n	n-1	s ²	s ² *(# obs -1)	(log(s ²))*(# obs -1)
1	12	0.083333333	11	5.00E+04	549998.917	51.68866
2	13	0.076923077	12	4.77E+04	572712.769	56.14507
3	13	0.076923077	12	4.77E+04	571959.231	56.13821
4	16	0.0625	15	4.00E+04	600471.750	69.03602
5	14	0.071428571	13	3.84E+04	499089.882	59.59506
6	15	0.066666667	14	4.33E+04	605977.733	64.90860
7	14	0.071428571	13	4.14E+04	538654.000	60.02576
8	14	0.071428571	13	3.86E+04	502438.857	59.63282
9	13	0.076923077	12	4.12E+04	494373.077	55.37848
10	14	0.071428571	13	3.76E+04	488592.929	59.47505
11	17	0.058823529	16	3.32E+04	531270.471	72.33913
12	15	0.066666667	14	3.74E+04	523470.933	64.01870
13	14	0.071428571	13	4.36E+04	566563.714	60.31097
14	16	0.0625	15	3.61E+04	541313.938	68.36037
15	15	0.066666667	14	3.87E+04	541965.333	64.22981
16	13	0.076923077	12	5.78E+04	694153.692	57.14729
17	16	0.0625	15	4.07E+04	610467.938	69.14357
18	15	0.066666667	14	4.40E+04	615985.333	65.00819
19	6	0.166666667	5	5.47E+04	273477.500	23.68976
20	6	0.166666667	5	6.31E+04	315740.833	24.00180

APPENDIX XIII.

3" WIDTH 20' CLEARS ADDED (INTERVENTION) - SNK

19	20	7	10	12	13	15	16	1	9	18	2	3	6	11	8	14	4	17	5	
		----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	5
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		----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	9
		----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	1
		----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	16
		----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	15
	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	13
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APPENDIX XIV.

3" WIDTH NUMBER OF BOARDS PROCESSED DATA MATRIX

		ALGORITHM																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955	955
	989	989	989	989	989	989	989	989	989	989	989	989	989	989	989	989	989	989	989	989	989
	997	997	997	997	997	997	997	997	997	997	997	997	997	997	997	997	997	997	997	997	997
2	2224	2229	2229	2224	2231	2231	2228	2240	2240	2228	2238	2239	2224	2271	2271	2276	2233	2266	2319	2219	2219
	2219	2228	2231	2220	2223	2223	2218	2227	2231	2230	2230	2231	2228	2243	2243	2252	2240	2236	2296	2218	2217
	2236	2238	2239	2233	2238	2239	2245	2238	2238	2272	2238	2245	2344	2289	2289	2267	2303	2261	2262	2238	2237
3	3269	3271	3271	3272	3271	3271	3439	3252	3193	3427	3251	3198	3434	3259	3259	3059	3550	3267	3064	3620	3635
	3282	3254	3254	3285	3287	3287	3293	3182	3066	3289	3180	3069	3324	3216	3216	3057	3331	3216	3057	3669	3678
	3309	3308	3308	3349	3349	3349	3318	3226	3164	3319	3204	3164	3421	3221	3221	3072	3389	3218	3072	3700	3685
4	7156	7146	7157	7157	7236	7553	7390	7186	7235	7288	7185	7527	7182	7210	7210	7527	7400	7245	7539	7156	7156
	7138	7164	7163	7126	7214	7477	7256	7203	7491	7184	7206	7474	7208	7201	7201	7474	7259	7227	7474	7153	7153
	7160	7162	7161	7224	7476	7507	7331	7428	7505	7354	7429	7501	7338	7429	7429	7501	7338	7429	7503	7171	7170
5	1158	1165	1167	1158	1159	1174	1162	1163	1171	1155	1154	1157	1161	1161	1161	1171	1161	1163	1171	1166	1166
	1174	1188	1197	1173	1203	1201	1174	1201	1198	1166	1191	1191	1178	1197	1197	1197	1181	1198	1201	1182	1182
	1179	1188	1192	1177	1190	1199	1179	1191	1199	1168	1179	1181	1179	1191	1191	1195	1179	1182	1195	1189	1189
6	3087	3069	3090	3133	3241	3272	3101	3085	3078	3090	3075	3188	3090	3082	3082	3133	3089	3088	3185	3227	3227
	3073	3065	3056	3071	3252	3303	3090	3074	3063	3065	3039	3094	3073	3067	3067	3073	3096	3074	3153	3222	3222
	3119	3111	3118	3291	3291	3320	3146	3112	3101	3115	3125	3195	3138	3138	3138	3147	3146	3140	3189	3289	3289
7	8892	8892	8892	8887	8887	8887	8854	8855	8855	8850	8850	8850	8865	8820	8820	8820	8722	8919	8919	8805	8805
	8731	8731	8731	8726	8726	8726	8750	8699	8699	8790	8629	8644	8684	8705	8705	8696	8922	8898	8890	8848	8825
	8911	8911	8911	8907	8907	8907	8884	8897	8897	9035	8882	8882	8773	8795	8795	8795	9441	9429	9420	8927	8894
MEAN		3821.81	3821.952	3824.19	3835.905	3872.476	3908.333	3857.095	3828.571	3836.429	3855.524	3820.286	3855.762	3837.476	3820.857	3831.19	3891.571	3866.619	3888.19	3901.905	3899.5

APPENDIX XV.

3" WIDTH NUMBER OF BOARDS PROCESSED - BARTLETT'S TEST

#	n	1/n	n-1	s ²	s ² *(# obs -1)	(log(s ²))*(# obs -1)
1	21	0.04762	20	8.22E+06	164369831.23810	138.29584
2	21	0.04762	20	8.22E+06	164359946.95238	138.29532
3	21	0.04762	20	8.22E+06	164300617.23810	138.29218
4	21	0.04762	20	8.21E+06	164285385.80952	138.29138
5	21	0.04762	20	8.32E+06	166479409.23810	138.40661
6	21	0.04762	20	8.52E+06	170456502.66667	138.61167
7	21	0.04762	20	8.36E+06	167133171.80952	138.44065
8	21	0.04762	20	8.30E+06	165962409.14286	138.37959
9	21	0.04762	20	8.46E+06	169154259.14286	138.54506
10	21	0.04762	20	8.41E+06	168121589.23810	138.49187
11	21	0.04762	20	8.27E+06	165344894.28571	138.34722
12	21	0.04762	20	8.51E+06	170175287.80952	138.59733
13	21	0.04762	20	8.23E+06	164539283.23810	138.30479
14	21	0.04762	20	8.28E+06	165618660.57143	138.36159
15	21	0.04762	20	8.54E+06	170761949.23810	138.62722
16	21	0.04762	20	8.71E+06	174253085.14286	138.80301
17	21	0.04762	20	8.79E+06	175749306.95238	138.87727
18	21	0.04762	20	8.99E+06	179792857.23810	139.07485
19	21	0.04762	20	8.17E+06	163356347.80952	138.24212
20	21	0.04762	20	8.14E+06	162792769.23810	138.21210

APPENDIX XVI.

3" WIDTH NUMBER OF BOARDS PROCESSED - SNK

11	14	1	2	3	8	15	4	9	13	10	12	7	17	5	18	16	20	19	6	
						----	----	----	----	----	----	----	----	----	----	----	----	----	----	6
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APPENDIX XVII.

3" WIDTH PERCENT PARTS RECOVERY DATA MATRIX

ALGORITHM

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	50.937	50.937	50.937	50.937	50.937	50.937	50.948	50.948	50.948	50.915	50.915	50.915	51.096	51.096	51.096	51.096	51.096	51.096	50.937	50.937
	49.475	49.475	49.475	49.475	49.475	49.475	49.475	49.475	49.475	49.492	49.492	49.492	49.530	49.530	49.530	49.530	49.530	49.530	49.475	49.475
	48.848	48.848	48.848	48.848	48.848	48.848	48.848	48.848	48.848	48.889	48.889	48.889	60.415	60.415	60.415	60.415	60.415	60.415	48.848	48.848
2	77.650	77.417	77.417	77.650	77.328	77.328	77.462	76.997	76.972	77.456	77.020	76.967	77.737	76.029	75.839	77.468	76.254	74.824	78.214	78.249
	77.868	77.489	77.346	77.862	77.696	77.354	77.936	77.499	77.329	77.621	77.374	77.320	77.702	77.028	76.631	77.476	77.343	75.444	78.284	78.296
	77.237	77.025	76.990	77.263	77.017	76.981	76.950	77.010	77.018	76.194	77.048	76.829	74.393	75.467	76.042	75.470	76.317	76.256	77.687	77.685
3	73.759	73.677	73.677	73.690	73.682	73.682	71.105	74.305	75.332	71.315	74.310	75.280	71.304	74.191	77.880	69.216	74.067	77.800	68.238	67.942
	73.493	73.969	73.969	73.401	73.326	73.326	73.797	75.639	77.776	73.889	75.673	77.700	73.358	75.094	78.008	73.266	75.094	78.001	67.317	67.167
	72.858	72.868	72.868	72.105	72.105	72.105	73.146	74.663	75.731	73.159	75.085	75.738	71.355	74.807	77.553	71.952	74.877	77.559	66.777	67.023
4	75.682	75.839	75.666	75.265	74.315	70.164	72.320	74.821	74.316	73.518	74.848	70.475	75.011	74.621	70.477	72.224	74.281	70.329	75.699	75.692
	75.962	75.556	75.579	75.700	74.608	71.123	74.088	74.774	70.936	75.095	74.751	71.158	74.671	74.814	71.155	74.004	74.564	71.153	75.749	75.756
	75.634	75.614	75.619	74.421	71.130	70.731	73.151	71.819	70.761	72.847	71.797	70.806	73.055	71.811	70.821	73.054	71.798	70.796	75.470	75.466
5	82.197	81.594	81.412	82.280	82.136	80.710	81.949	81.756	81.032	82.571	82.664	82.362	82.061	81.942	80.959	82.006	81.722	80.945	81.569	81.569
	80.780	79.484	78.763	80.834	78.253	78.376	80.680	78.401	78.579	81.650	79.244	79.186	80.390	78.766	78.719	80.091	78.645	78.336	79.999	79.999
	80.317	79.497	79.198	80.534	79.272	78.597	80.325	79.289	78.649	81.387	80.322	80.136	80.320	79.262	78.851	80.414	80.005	78.879	79.468	79.468
6	77.730	78.027	77.647	76.714	74.521	73.906	77.391	77.689	77.800	77.614	77.784	75.459	77.604	77.722	76.584	77.612	77.588	75.550	74.883	74.883
	77.910	78.053	78.222	77.936	74.401	73.520	77.622	77.898	78.088	78.061	78.535	77.368	77.907	78.008	77.836	77.516	77.898	76.261	74.994	74.994
	77.027	77.172	77.017	73.719	73.678	73.156	76.440	77.138	77.378	77.081	76.787	75.326	76.612	76.574	76.299	76.459	76.505	75.469	73.861	73.861
7	74.350	74.350	74.350	74.404	74.404	74.404	74.815	74.800	74.800	74.894	74.901	74.901	74.678	75.107	75.107	75.354	74.062	74.062	75.173	75.178
	75.903	75.903	75.903	75.952	75.952	75.952	75.923	76.292	76.292	75.679	76.979	76.845	76.485	76.225	76.336	74.200	74.489	74.588	75.372	75.353
	74.391	74.391	74.391	74.445	74.445	74.445	74.730	74.568	74.568	73.638	74.742	74.742	75.408	75.346	75.346	70.539	70.669	70.711	74.503	74.593
MEAN	72.857	72.723	72.633	72.544	71.787	71.196	72.338	72.601	72.506	72.522	72.817	72.281	72.909	73.041	72.928	72.351	72.725	72.286	71.548	71.544

APPENDIX XVIII.

3" WIDTH PERCENT PARTS RECOVERY - BARTLETT'S TEST

#	n	1/n	n-1	s ²	s ² *(# obs -1)	(log(s ²))*(# obs -1)
1	21	0	20	9.92E+01	1983.66058	39.92875
2	21	0	20	9.70E+01	1939.15163	39.73164
3	21	0	20	9.58E+01	1916.63503	39.63019
4	21	0	20	9.77E+01	1954.18030	39.79869
5	21	0	20	9.13E+01	1826.66249	39.21257
6	21	0	20	8.80E+01	1760.40022	38.89163
7	21	0	20	9.70E+01	1939.68685	39.73403
8	21	0	20	9.58E+01	1916.34061	39.62885
9	21	0	20	9.64E+01	1927.46844	39.67915
10	21	0	20	9.94E+01	1988.16097	39.94843
11	21	0	20	9.85E+01	1970.15514	39.86941
12	21	0	20	9.69E+01	1938.09801	39.72691
13	21	0	20	7.59E+01	1517.22625	37.60041
14	21	0	20	7.35E+01	1469.73421	37.32418
15	21	0	20	7.51E+01	1501.98058	37.51269
16	21	0	20	7.48E+01	1496.34968	37.48006
17	21	0	20	7.33E+01	1465.55455	37.29944
18	21	0	20	7.20E+01	1440.70480	37.15090
19	21	0	20	9.78E+01	1956.13215	39.80736
20	21	0	20	9.79E+01	1958.19593	39.81652

APPENDIX XIX.

3" WIDTH PERCENT PARTS RECOVERY - SNK

6	20	19	5	12	18	7	16	9	10	4	8	3	2	17	11	1	13	15	14	
	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	14
	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	15
	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	13
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	1
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	11
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	17
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	2
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	3
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	8
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	4
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	10
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	9
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	16
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	7
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	18
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	12
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	5
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	19
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	20
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	6

APPENDIX XX.

3" WIDTH YEARLY VALUE DIFFERENCES FROM ALGORITHM 14

Algorithm Number	Value/Fbm	Yearly Value Difference From Algorithm 14
1	0.75567	-\$16,346.52
2	0.75482	-\$21,308.85
3	0.75423	-\$24,753.30
4	0.75416	-\$25,161.96
5	0.75027	-\$47,871.94
6	0.74685	-\$67,838.04
7	0.75285	-\$32,809.79
8	0.75418	-\$25,045.20
9	0.75438	-\$23,877.59
10	0.73017	-\$165,216.58
11	0.73302	-\$148,578.16
12	0.72897	-\$172,222.23
13	0.75696	-\$8,815.44
14	0.75847	0.00
15	0.75814	-\$1,926.55
16	0.75428	-\$24,461.39
17	0.75719	-\$7,472.69
18	0.75493	-\$20,666.67
19	0.7476	-\$63,459.51
20	0.74746	-\$64,276.84

APPENDIX XXI.

EXAMPLE OF 3 WAY VALUE/FBM ANOVA SETUP

CUTTING BILL	repl.	ALGORITHM 1 (1 part - 70%)			ALGORITHM 2 (1 part - 80%)			ALGORITHM 3 (1 part - 90%)		
		5 mins.	10 mins.	15 mins.	5 mins.	10 mins.	15 mins.	5 mins.	10 mins.	15 mins.
1	1	1.346	1.725	1.713	1.237	1.463	1.116	1.361	1.376	1.424
	2	1.278	1.021	1.367	1.551	1.370	1.306	1.692	1.279	1.666
	3	1.370	1.587	1.486	1.500	1.880	1.610	1.560	1.727	1.771
2	1	1.418	1.809	1.488	1.521	1.573	2.139	1.657	1.811	1.777
	2	1.285	1.835	1.887	2.032	1.267	1.291	1.363	1.054	1.554
	3	1.248	1.311	1.561	1.527	1.467	1.655	1.429	1.578	1.752
3	1	1.522	1.469	1.344	1.349	1.892	1.876	1.741	1.669	1.588
	2	1.372	1.385	2.051	1.463	1.722	1.397	1.354	1.477	1.226
	3	1.401	1.298	1.905	1.899	1.901	1.599	1.425	1.612	2.099